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A constraint-based approach for assessing the capabilities of existing designs to handle product variation

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A CONSTRAINT-BASED APPROACH FOR ASSESSING THE CAPABILITIES OF EXISTING DESIGNS TO HANDLE PRODUCT VARIATION

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ABSTRACT

All production machinery is designed with an inherent capability to handle slight variations in product. This is initially achieved by simply providing adjustments to allow, for example, changes that occur in pack sizes to be accommodated, through user settings or complete sets of change parts. By the appropriate use of these abilities most variations in product can be handled. However when extreme conditions of setups, major changes in product size and configuration, are considered there is no guarantee that the existing machines are able to cope. The problem is even more difficult to deal with when completely new product families are proposed to be made on an existing product line. Such changes in product range are becoming more common as producers respond to demands for ever increasing customization and product differentiation.

An issue exists due to the lack of knowledge on the capabilities of the machines being employed. This often forces the producer to undertake a series of practical product trials. These however can only be undertaken once the product form has been decided and produced in sufficient numbers. There is then little opportunity to make changes that could greatly improve the potential output of the line and reduce waste. There is thus a need for a supportive modelling approach that allows the effect of variation in products to be analyzed together with an understanding of the manufacturing machine capability. Only through their analysis and interaction can the capabilities be fully understood and refined to make production possible.

This thesis presents a constraint-based approach that offers a solution to the problems above. While employing this approach it has been shown that, a generic process can be formed to identify the limiting factors (constraints) of variant products to be processed. These identified constraints can be mapped to form the potential limits of performance for the machine. The limits of performance of a system (performance envelopes) can be employed to assess the design capability to cope with product variation. The approach is successfully demonstrated on three industrial case studies.

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Terminology

The page introduces the definitions of the terminology used in this thesis. Many of the terms are common across the discipline described in the document.

Term	Description
Envelope of Opportunity	*Is the area where the design will function after external modification to configuration. (Matthews et al, 2006)*
Envelope of Performance	*Is the area where the machine will function, using only the inherent design adjustments. This envelope has also been termed as the capacity or capability envelope (Shewchuk and Moodie, 1998).*
Performance	*The capability to satisfactorily complete a specific task e.g. Accuracy in developing a kinematically specific output (path following, function generation, rigid body guidance etc) Cutkosky (2005)*
Producer	*This term is used to identify to user of the piece of equipment under investigation*
Process flexibility	*Variation in product can be compensated in the manufacturing process without penalty; performance or product redesign. Athey and Schmutzler (1995)*
Product Family	*A product concept that is designed for a market but caters for the individual wishes of customers by introducing variety within a defined product architecture and within a defined manufacturing process . Erens (1996)*
Product Variant	*An occurrence of a product family, sometimes introduced as a product of its own, sometimes derived from a product family on customer order. Erens (1996)*
Manufacturer	*This term is used to identify the manufacturer of the equipment under investigation*
Single-Product	*A product that hardly any 'pre-defined' relationship with other products. Any resemblance with other products is mainly coincidental or due to the style of the maker. Erens (1996)*

Chapter 1

Introduction

"Usually, if you have a new idea, you very rarely break through to anything like recognizable development or implementation of that idea the first time"
Martin Fleischmann

All production machinery, whether from food processing, automotive sub-component assembly or electrical device sectors, is designed with an inherent capability to handle slight variations in product. This is initially achieved by simply providing adjustments to allow, for example, changes that occur in pack sizes to be accommodated, through user settings or complete sets of change parts. By the appropriate use of these approaches most normal variations in product setting can be handled. However when extreme conditions of setups, major changes in product size and configuration, are considered there is no guarantee that the existing machines are able to cope. The problem is even more difficult to deal with when completely new product families are proposed to be made on a producers existing product line.

Such changes in product range are becoming more common as producers respond to demands for ever increasing customization and product differentiation. Within the process and packaging industries range changes are often achieved through variation in product packaging formats, numbers in a pack and the types of presentation employed, particularly in the supermarkets (Hanlon *et al,* 1998). All result in the producer being forced to make more and more frequent changes to the line with little to no guidance on how this can be achieved (or even if it is at all possible). The lack of knowledge on the capabilities of the machines being used forces the producer to undertake a series of practical product trials. These however can only be undertaken once the product form has been decided and produced in insufficient numbers. There is then little opportunity to make changes that could greatly improve the potential output of the line and reduce waste. Research by Rigamonti and Tolio (2004) shows that from a machine manufacturers point of view, system configuration is the cornerstone in the offer of processing capability to their customers. But the authors noted that only 15% are followed by an order. So the configuration phase is an expensive task for the machine manufacturer.

1.1 TOPIC OF RESEARCH

Traditional production machine design is directed towards the creation of a single embodiment to meet a given specific performance requirement (Hicks *et al*, 2001a). This means that the design is only known to be able to accomplish the task for which it was originally intended. Its ability to perform related, variant tasks is uncertain. Industry now competes in a truly global market place; mass customisation has come to the fore Tseng, and Jiao (2001). Manufacturers now need to produce a family of products which vary from the existing design, sometimes in only minor ways. In the past this has lead to the producers purchasing new equipment to handle these product variations. This puts a high financial burden on companies already trading in a highly competitive sector. It is common in many industrial situations that companies are attempting to develop a range of machines to meet different customer’s needs without a full understanding of the nature of their products and the global issues involved.

There is thus a need for a supportive modelling approach that allows the effect of variation in products to be analyzed together with an understanding of the manufacturing machine capability. Only through their analysis and interaction can the capabilities be fully understood and refined to make production possible. Figure 1.1 graphically shows the understanding the research is attempting to identify. With the machine setup and performance factors established, there is a known capability of the machine, but, what if the user wants to process a variant product?

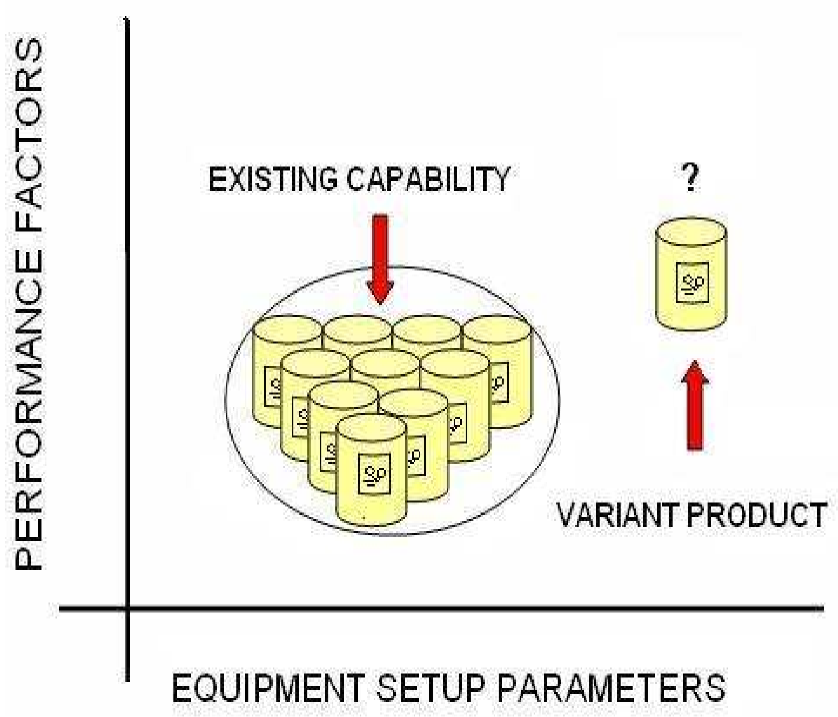


Figure 1.1 Processing capability

1.2 MANUFACTURING EQUIPMENT DESIGN

This research is concerned with the types of machine design that take place in small to medium sized companies (This has been due to the availability of case studies). Very often such companies have a base range of products which they offer. However the resources are such that there is not the expertise or time available to perform any in-depth analysis of how well the design operates or what constraints there are on its performance. Examples of such companies occur within the food processing and packaging machine sectors (Hanlon *et al*, 1998). Figure 1.2 shows some examples of such equipment. The picture top left shows a carton erection machine, used to collate and pack cakes. Top right is a box carton folding machine, used to construct a box around product. Bottom left is a carton folding machine, the picture in the middle is a typical over-wrapping machine, used to film wrap items such a CD cases and bottom right is a double ‘fish-tail’ confectionary wrap machine.

Figure 1.2 Example machinery

Such machinery is often constructed of multiple individual and connected mechanisms to translate a variety of motions in processing a product. From this point forward in the thesis any mechanism which interacts with product is referred to, as a “machine”. This definition aligns with work present by the German kinematician, Reuleaux (1891), who defines a machine as a *“combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motions”.*

The design of machines involves a large number of interdependent tasks which relate either to the artefact itself or the processes and systems by which it is too developed and produced. These tasks are generally represented as process models and include models of design (Pahl and Bietz, 1996) design and manufacture (Zied, 1991), product life-cycle (Pugh, 1991) and of the manufacturing system or production system (Huda and Chung, 2003). At a conceptual level, all of the tasks can be considered to involve some form of problem solving, where a solution is sought that best achieves a set of requirements or goals given a variety of constraints and an available set of elements or alternatives. The elements could include for example mechanical components, manufacturing cells or other available resources. Such activities are inherently time-consuming, require a detailed understanding and are often analytically intensive. For these reasons many attempts have been undertaken by academia and industry to develop supportive tools and methods for particular classes of activity or specific problems. Examples of such approaches include: knowledge based, engineering systems (Chapman and Pinfold, 1995), simulation models for transmission (Hicks *et al,* 2005), hydraulic systems (Darlington, 1998) and configuration tools (Potter *et al,* 2001).

In general these tools and their underlying methods employ a variety of fundamentally different techniques to represent the system under consideration. This includes handling the system elements and relationships, the goals or objectives and the strategy for determining a solution. The latter of these may be either a fully or partially automated process. For example, AMESim and Scheduling or configuration modelling and DFMA (Boothroyd *et al*, 2001) all involve representing a system and relationships, and then determining an appropriate configuration. This variety in underlying methods is not only prevalent across different tasks but also the various tools which perform the same or similar task. For example, SWORDS (Mullineux, 2001) and CAMLINKS™ both represent and handle mechanisms and linkage assemblies but the underlying methods are very different. CAMLINKS™ explicitly calculates the kinematics of the system whilst SWORDS determines a system state using constraint rules from which the kinematic properties may then be calculated.

One of the main reasons for this variety of underlying methods is that particular tools or techniques are frequently driven by the perspective of the particular problem and how it is to be solved rather than a generalised approach for reasoning about the problem. "It is arguable that such variety makes the use, integration, exchange and unification of supportive tools, methods and processes (process elements) particularly difficult and contributes too many of the research challenges facing academia and industry" (Culley, 1999).

1.3 LIMITS, BOUNDS AND CONSTRAINTS.

With the concluding remarks from section 1.2 in mind, there is a group of methods that are emerging as a more generalised approach for modelling and reasoning and have been recently applied to a range of different tasks associated with design and manufacture. These approaches are constraint-based reasoning and constraint modelling. The approach involves representing what is to be achieved rather than how it is to be achieved, and/ or how that achievement is to be thought about and typical employs numerical techniques to fully or partially satisfy the constrained problem. For these reasons, constraint techniques potentially offer an opportunity for a more generalised approach to the modelling and reasoning about products or machines during design and manufacture, which could support a more unified model for the entire design and manufacturing process.

Constraints have previously been discussed in the design theory by Suh (1990), Ullman (1992) and Pahl and Bietz (1996), within the modelling context, Lin and Chen (2002) highlight the core element of the design process is the recognition, formulation, satisfaction and optimal solution of the constraints, which are constantly added, removed and modified. Previous authors have labelled constraints in different ways: in the design context Lin and Chen (2002) summarise that, a constraint is "*either a bound on a single design parameter or the relation among a set of design parameters*". Within the context of this thesis, any further reference to constraints the definition used is that proposed by Goldratt (1990) who states that, "*a constraint is anything that limits the performance of a system*".

1.4 PRODUCT VARIATION

The manufacturing sector is driven by many factors. These include an increasing need to satisfy customer demands for greater product variety and for more responsive, small batch delivery (mass customization). Products that are very similar in their general structure but differ in the details of each customer-specific variant can be grouped into general product families structures (PFS). With the increasing uncertainties with which manufacturers are facing the unpredictable market environment, more changeability is required of the manufacturing systems in order to keep productivity at an acceptable level. However, the customer-driven market is not the only source for uncertainties and disturbances. In addition to the downstream disturbances introduced by the market, manufacturers have to cope with variability in machine performance (internal disturbances) and disturbances introduced by for example raw material quality variation (upstream disturbances).

This research is interested in the assessment for product variation, this includes of the nature of design changes, the certainty associated with a given type of change, and the occurrence of a specified type of change. With reference to Scewchuk and Moodie (1998), this gives change under three categories:

- *Changes in production requirements*: changes in product definition, product mixes, production scenarios, or various combinations of these
- *Changes in system input*: changes in input definitions (e.g., material condition out-of-specification, incorrect dimensions, tolerances, geometry, etc)
- *Changes in the system itself*: changes in the capabilities available, or system configuration, due to component wear and unreliability.

This research is only concerned with the first two change scenarios, which are variant product related. The above changes can be further classified under two headings; planned and unplanned variety. The changes in production requirement can be sub-divided into the planned variety heading, and changes in system input and changes in the system itself, under the unplanned heading.

An example of the type of problem this research will cover is shown in figures 1.3 and 1.4. The initial machine has been design with an inherent flexibility to package four different yellow fat products (cf. figure 1.3). Each of these has a different package base and lid configuration and within this part (b) shows there is also a different pack consistency for the same product. Now the question was then raised, as to whether there is the capability in the machine to pack the product in figure 1.4.

This presents issues as there is a larger size tub, and it has different pack size and pack configuration.

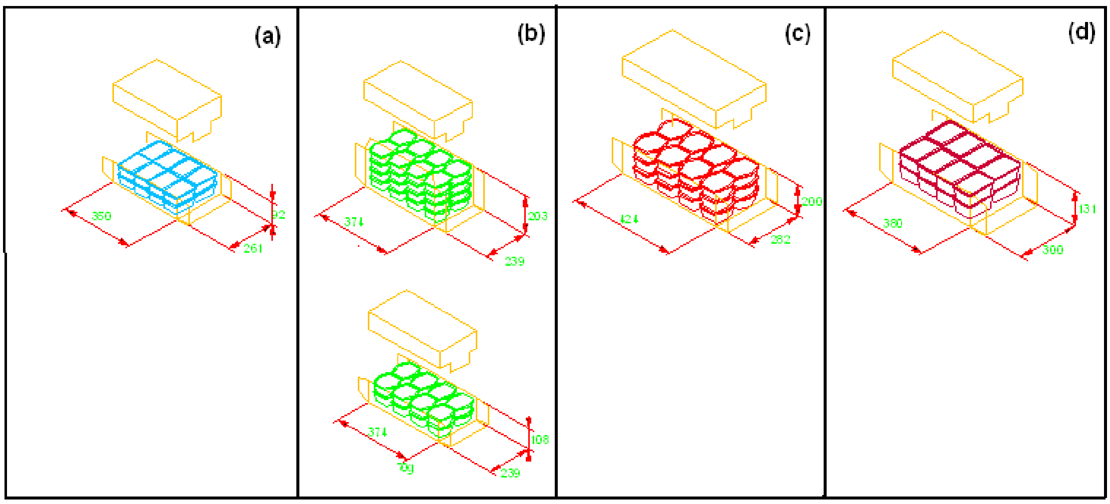


Figure 1.3 Standard pack configurations

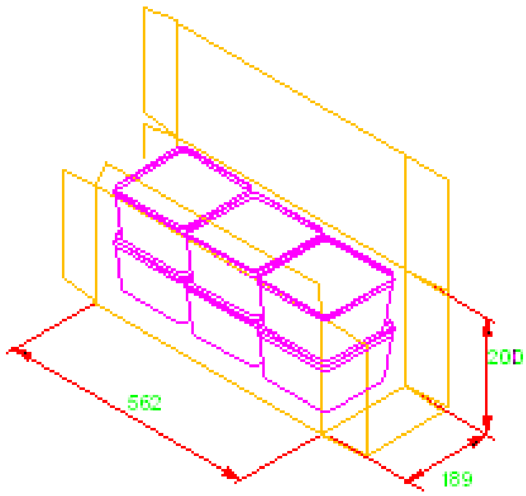


Figure 1.4 Variant product

1.5 GOALS OF THE RESEARCH

The previous sections have identified the need for manufacturing companies, to establish, not only the inherent capability of the processing system but also the potential processing capability of the system. To this extent this research looks to investigate three hypotheses:

Hypothesis 1

"A generic process can be formed to identify the limiting factors (constraints) of variant products to be processed"

Hypothesis 2

"The identified limiting factors (constraints) can be mapped to form the potential limits of performance for a system"

Hypothesis 3

"The limits of performance of a system (performance envelopes), can be employed to assess its design capability to cope with product variation"

In order to investigate these hypothesises, a number of key objectives have been identified:

1. To investigate contemporary modelling approaches and software for engineering systems, with prime consideration to the mechanisms employed in manufacturing systems. Investigate methods for representing the data generated by modelling and analysis of system. Analyse previous applications of limits, bounds and constraints in manufacturing and design applications.

2. To demonstrate the effectiveness of product and process constraints in the design and manufacturing domains.

3. To investigate the relationships of the product and processing constraints.

4. To investigate an approach where, the performance envelopes of an existing machine can be established.

5. To investigate an approach where, with the performance envelope established, they can be used to assess the machines ability to process variant products.

6. To validate the approach through its application on industrial case studies.

These objectives are addressed by the work presented in each of the chapters. The research presented in this thesis has also generated a number of peer reviewed publications. The abstracts of these can be seen in appendix F.

1.6 OVERVIEW OF THESIS.

This chapter has presented with a broad introduction to the research. It has identified the key industrial benefits of obtaining the objectives presented. This thesis consists of nine chapters and there five appendices. The thesis is into four phases, as shown in figure 1.5.

- Phase 1, introduces the research topic and related work in this research field;
- Phase 2, introduces the mains theories behind the research to the reader;
- Phase 3, presents the implementation strategy and case study examples, and
- Phase 4, summarizes the work and offers potential areas of future work.

A chapter by chapter breakdown follows the figure 1.5

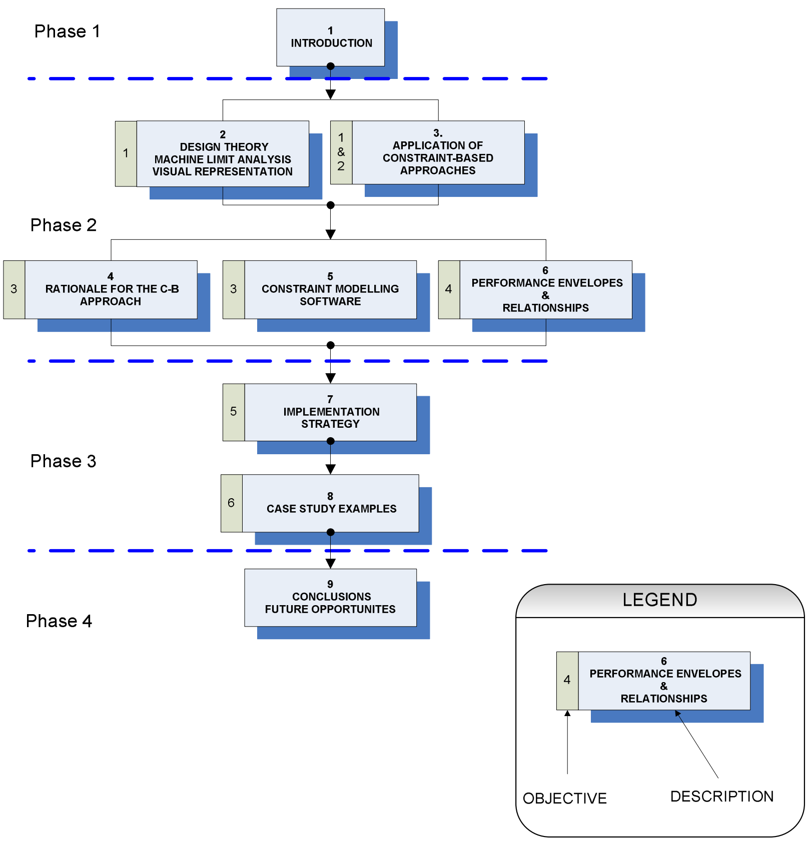


Figure 1.5 Thesis structure

Chapter 2 The chapter starts with a review of engineering design. Encompassed in this are, the fundamental theories, practices and prime technologies that are relevant to the research presented in this thesis. The chapter starts with the fundamental theories, following this are the methods of modelling and analysis which have been employed in the design process. The chapter also examines and identifies weaknesses in approaches that have been applied in finding the working and performance limits of machines and systems. The need has been identified to represent the design knowledge of performance envelopes of the mechanisms that have been investigated. There is also a section on visual representation of such information. All literature reviewed is critically assessed in respect of the problem identified in this thesis.

Chapter 3 The core element of this thesis is the application of a constraint-based approach. This chapter sets the precedence for the use of constraint-based approaches. Showing knowledge of constraints can be employed throughout the product life cycle. As with chapter 2 the literature reviewed is critically assessed in respect of the problem identified in this thesis.

Chapter 4 This chapter presents the core theory behind the approach being employed. It explains the rationale for choosing a constraint-based approach to answer the hypothesis given in section 1.5. Also presented in this chapter is a taxonomy of failure mode constraints which have been identified for the product being processed and for the processing equipment.

Chapter 5 This section provides an overview of the constraint-based modelling package employed. It explains how constraint-based reasoning is used in the construction of models and simulations of systems. The chapter also identifies the specific constraints related to the machinery that the modelling software has to deal with.

Chapter 6 This chapter builds on the previous chapter by explaining the concept of performance envelopes and show the relationships for the failure mode constraints identified in chapter 3 and the process equipment. The chapter shows how the recognized constraints for product and process are employed to identify the ability of the processing equipment to handle a variant product.

Chapter 7 This chapter presents the implementation strategy for the constraint-based modelling approach. It explains how the constraints are employed at various levels to construct and test the ability of a given machine to perform the variant tasks required to process the new product.

Chapter 8 This chapter presents case study examples of the approach. These examples are broken down to show how the relative attributes of the approach are used to identify solutions to the respective problems of each example.

Chapter 9 This chapter revisits the initial problem identified in chapter 1 of this thesis and summarises the findings that have been presented. This enables the work to be placed into context with current research and identifies how knowledge about this subject has improved as a result of it. A critical appraisal of this thesis identifies a number of research areas which remain outstanding and therefore require future work.

Appendix A This contains the constraint modelling full code for Case study 1: the sweet wrapping machine.

Appendix B This presents some of the main functions of the constraint modelling software employed within this thesis.

Appendix C This presents the model space hierarchy diagrams for case studies 2 and 3 of chapter 7.

Appendix D This documents the additional investigations undertaken for case study 3. This shows the product constraints identification and optimal motion curve analysis.

Appendix E Presents an overview for constraint handling techniques, which are noted in the reviews of chapter 3.

Appendix F This presents the peer reviewed publications which have been generated during this research.

Chapter 2

Background

"History should be regarded as a means for understanding the past and solving the challenges of the future"
Mark Foley

It is important to have a clear idea of the prior research which relates to the topic of this thesis. As the research is investigating the ability of systems to handle variation in product, this issue straddles two domains: the 'process flexibility' of manufacturing equipment and the design of manufacturing equipment. To this end, an investigation of the relevance of design theory is presented along with the prior techniques employed to find and present process capability. This then leads to the understanding and assessment of the performance limits of the machine to be investigated. Techniques from engineering domains employed in finding the limits of systems presented, and critically reviewed in their effectiveness. As the findings need to be analysed and presented, the current and past techniques for this are identified and reviewed. This chapter fulfils objective one from chapter one.

2.1 ENGINEERING DESIGN.

Feilden (1963) states that: *"Engineering design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency".* This section describes some of the main theories of engineering design, and presents the specifics of design variation and the design of machinery.

2.1.1 Theories and approaches

Design theory is generic across disciplines, the basic principles and concepts apply across all branches of engineering. Although the underlying principles of design remain the same the approaches to design process change. Design theories fall into two categories: prescriptive and descriptive. Descriptive design describes current practice whereas prescriptive design describes how design should be done. Cross (1989) states that "prescriptive approaches are intended to encourage the designer to adopt improved ways of working". Prior research has shown that three distinct types of design activities exist (Pahl and Bietz, 1996): *Original design*- which uses original solution principles to solve the functions and sub-functions of the problem. *Adaptive design*- which adapts existing solution principles to solve the functions and sub-functions of the problem, and *Variant design*- which varies the details of existing design to solve problems. Findings by Pahl and Bietz shows that 55% of products are based on adaptive design, 25% are based on new design and the remaining 20% on variant design. Following are some of the design approaches and theory modifications.

The systematic approach was predominately developed in Germany after the second world war, it offers a structured approach to the design process. Pahl and Beitz (1996) report the four main steps of design activities to be: Clarification of task, Conceptual design, Embodiment layout and Detailed design. Each of these steps can be further detailed in sub-steps with associated working methods. This approach has been documented into the VDI design directives (Pahl and Beitz, 1996). Here the engineering design process is regarded as a sequence of activities leading to intermediate results (performance specification, function structure, principle solution, modular structure, preliminary layout, definitive layout and documentation) as represented in figure 2.1.

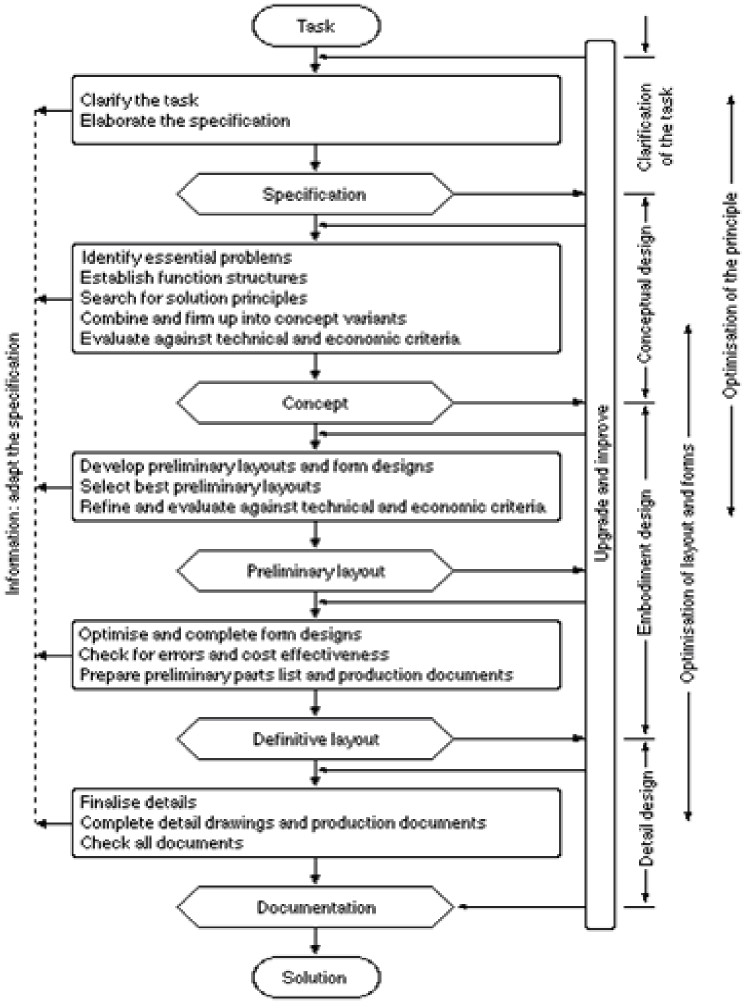


Fig 2.1 Pahl and Beitz (1996) model of design process

The general design theory developed by Yoshikawa (1981). This utilises set theory to model the design knowledge and design process. This is a descriptive design approach. The emphasis of this approach is based on the structuring of the design knowledge offering a greater understanding of the design process. *The axiomatic approach of design* by Suh (1990). This approach identifies general principles which govern good design solutions. These principles are formalized in terms axioms and theorems. This is a descriptive approach, which attempts to add design rules to the process: minimize information content and maintain functional independence while predicting some properties of designed objects.

There are four main concepts in axiomatic design - domains, hierarchies, zigzagging, and design axioms.

Domains: The designer following the axiomatic design process (cf. figure 2.1). Produces a detailed description of what functions the object is to perform, a description of the object that will realize those functions, and a description of how this object will be produced.

Table 2.1 Mapped design phase and domain(Suh, 1990)

Design phase	Design domain	Design elements/Phase activity
	Customer domain	- customer needs (CNs), the benefits customers seek
Concept design		- customers' needs are identified and are stated in the form of required functionality of a product.
	Functional domain	- functional requirements (FRs) of the design solution - additional constraints (Cs)
Product design		- a design is synthesized to satisfy the required functionality.
	Physical domain	- a design is synthesized to satisfy the required functionality.
Process design		- a plan is formulated to implement the design.
	Process domain	- process variables (PVs)

Hierarchies: The output of each domain evolves from abstract concepts to detailed information in a top-down or hierarchical manner.

Zigzagging: The designer goes through a process whereby he/she zigzags between domains in decomposing the design problem. The result is that the hierarchical development process in each domain is performed in conjunction with those in the other domains.

Design axioms: There are two design axioms about the relations that should exist between FRs and DPs which provide a rational basis for evaluation of proposed solution alternatives and the subsequent selection of the best alternative. *Independence Axiom*: maximize the independence of the functional requirements and *Information Axiom:* minimize the information content of the design and/ or maximize the probability of success.

The mathematical theories of design such as, Maimon and Braha (1998) consider real design process as an evolutionary process. This approach uses two different mathematical descriptions up to study respectively the idealized and real designs. The idealized design process is modelled using set theory and topology notations which are similar to the general design theory developed by Yoshikawa. The method devised by French (1971) is employed at the conceptual stage of design. He divides the process into phases which he calls 'schemes'. It is the individual schemes that make the greatest demands on the designer, and where there is the most scope for striking improvements. He sees the conceptual stage as the most important and states "It is the phase where engineering science, practical knowledge, production methods, and commercial` aspects need to be brought together, and where the most important decisions are taken".

The universal design theory, by Grabowski (1999), is a modified *systematic design approach*. As with Pahl and Beitz (1996), Grabowski views the design process as a number of structured stages. It is more a prescriptive methodology rather than a descriptive design theory. It intends to model design process knowledge and focus on how design should be done as a procedure. Another systematic design approach is that of Pugh (1981) with his *Total design theory.* Pugh advocates a matrix-based approach to multi-attribute design that permits design evaluation by comparing alternatives to a selected datum. This method is mainly employed for design concept selection. Samuel and Weir (1999), offer a systematic approach of analysing the design problem as systems made up of simpler constituents, and evolving a solution from known experience of such building blocks. The approach places emphasis on the concept of failure, and its avoidance - is also examined in detail the importance not only of contemplating expected failure conditions at the design stage but also checking those conditions as they apply to the completed design is stressed.

TRIZ (Russian phase: "Teoriya Resheniya Izobretatelskikh Zadatch") the theory of inventive problem solving, as first proposed by Altshuller (1994). This methodology offers a framework to stimulate creative design solutions. TRIZ provides tools and methods for use in problem formulation, system analysis, and failure analysis. TRIZ, in contrast to techniques such as brainstorming aims to create an algorithmic approach to the invention of new systems, and the refinement of old systems. Cross (1989) developed a prescriptive methodology where the design problem can be reduced into sub-problems and by solving the sub-problems an overall solution can be from. This methodology is very adaptive and actually prescribes little except a set of three rules, 1) adopt a framework; 2) select design methods to flesh out the framework; and 3) continually review and update the framework during the development effort. From the set of rules, Cross suggests that the design framework should be made up of six basic steps: clarifying objectives; establishing objectives; setting requirements; generating alternatives; evaluating alternatives and improving details. Using the six steps it can be seen that the design process is almost sequential.

2.1.2 Design and variation

Research into product variation has become popular over the last decade, although it is predominately product based. Designs for variety (DFV) are methodologies to reduce the issues and impacts related to the life cycle costs of production. The processes attempt to predict customer needs and to standardise products (Martin and Ishii, 1996, 1997). These approaches are purely aimed at the product and relate to Shingo (1981) and his work on mass customisation. Research into the ability of the production process to handle change normally falls under the design for changeover (DFC) area (Riek et al, 2006). Although the emphasis of this line is cost reduction by improved methodologies for change parts within the system, work by Pahl and Beitz (1996) identified that only 25% of design activities are new designs. Other design activities are made up of adaptive and variant designs. *Variant design* refers to a design activity where only the dimensions or arrangement of parts are varied for a product that already exists. The Similarity laws also noted by Pahl and Beltz (1996) offer design relationships of at least one physical dimension when a part is increased/ decreased in size. (pantograph construction). They state that geometric magnification is only permissible when the similarity laws allow. The similarity laws can be thoughts of as, constraints to the design of product families.

2.1.3 Machine specific design

The scale and complexity of machines may have changed since the industrial revolution, but the fundamental principles of the individual assemblies remain largely unaltered (Hicks *et al,* 2002). The reliance on such machinery for the production of consumer goods has received much attention from both academia, (Shigley and Uiker, 2003; Rosenauer, 1956); Tinoshenko and Young, 1948) and industry with PTC's ProEngineer and Unigraphics with its NX3. At the basic level, machines are constructed from a variety of mechanisms, the process of mechanism design for a function, is termed *synthesis,* that is the determination of form/ topology such as degrees of freedom, the number and type of links, the number and type of joints and the interconnections between links and joints. While some of these properties can be readily obtained from basic mechanism equations, there exists no mathematical model that can be used to determine completely the interconnections of links and joints, or to find suitable mechanism types uniquely. The number of possible mechanisms for a given problem increases rapidly as the number of links increases, and the number becomes significantly higher still if different types of joints are also included. There are four common synthesis tasks:

- *Path generation synthesis,* mechanism point, generates a particular path or passes through a series of positions.
- *Rigid body guidance synthesis,* to situate an element in a series of defined positions and orientations.
- *Type synthesis,* method by which objects are selected to form correct configurations.
- *Dimensional synthesis,* calculate the dimensions of components in the mechanism.

The synthesis of mechanisms is well documented for example, Freudenstein (1955, 1956) developed methods, by which a four-bar linkage can be designed to generate a function which is exact over a small number of points called precision points but which is approximate between these points. Rosenauer (1956) developed a method, where a four bar linkage can be designed to give prescribed instantaneous values of angular velocity and of angular acceleration. Current research into the above is mainly led by the IFToMM (International Federation for the Theory of Mechanisms and Machines) community. Their emphasis has been to promote research and development in the field of machines and mechanisms by theoretical and experimental methods, along with their practical application. The community's work is generally presented in three IFToMM publications: The International Scientific Journal of Gearing and transmission, the Journal of Problems in Mechanics and the International scientific Journal of Computational Kinematics. The emphasis of the current research is in the fields of robots and mechanism, such as Gallardo *et al,* (2007) most of this work is building on prior research such as Merlet *et al,* (1995) and Gosselin *et al,* (1992), and this is described in following sections.

Other contemporary research in machine systems has principally concentrated on the investigation and simulation of manufacturing system rather than the discrete assemblies that make up the whole system, such as Vigrat and Villeneuve (2005). A recent large scale European project SPECIES (RobuSt **P**roduction System **E**volution **C**onsidering **I**ntegrated **E**volution **S**cenarios), who's emphasis is directed towards: The qualitative and quantitative analysis of the influence of changeability and reconfigurability, at the production system level, on the manufacturing strategies of modern companies, and, the characterization of evolution scenarios of products, processes and systems in the manufacturing field, using a holistic viewpoint, which takes into account their joint evolution. The results of this research are to be presented in 2011 at the CIRP annual congress. Initial conference papers such as Rigamonti and Tolio (2006); Cunha (2005) and, Norman and Smith (2006) have stated the need for the research, and some preliminary analysis. In Tolio and Valente (2007) a stochastic approach is considered for machining operation systems for the manufacture of part families. Much of their research is directed at a manufacturing systems and operation level, and little consideration has been given to date to the discrete core machine elements, which is addressed in this thesis. They have also defined the approach of designing a new machine for flexibility, as focused flexibility manufacturing systems, FFMS (Tolio and Valente, 2006). Their research is also aimed at the design and manufacture of new equipment, at present no thought is given to equipment that has already been purchased and is in operation within production facilities. The work of this thesis is in the general area of the SPECIES project and indeed some of the findings reported in this thesis were presented in the SPECIES special session at the Digital Enterprise Technology conference (DET2007), Bath, UK.

2.1.4 Discussion

This sub-section has shown there exists, a variety of design theories professing to answer the design problem. What all the approaches show, is that design is essentially a problem solving activity. Some are more useful at different stages of the design activity such as TRIZ (Altshuller, 1994) for conceptual design, but the common factor to all the approaches mentioned above is that, they offer more knowledge of the design process.

2.2 MODELLING, SIMULATION AND ANALYSIS OVERVIEW

The follow section describes the main modelling approaches modelling approaches available for representing function, geometry, behaviour and performance of engineering systems. The section also introduces a variety of commercial and research computer aided design packages which can be employed when simulating and modelling mechanisms, machines and systems. While investigating modelling and simulation techniques, it becomes obvious that there are four specific issues that the engineer requires:

- *Accuracy and ability to model in detail*
    - A model is useless if it cannot model to the actually required
    - Amounts of time may be wasted using an unsuitable tool
- *Power and flexibility*
    - Need to build models quickly and incorporate all requirements
    - There is always going to be uncertainty in every project
- *Ease of understanding for validity*
    - Extensive output from model is valid
    - High quality interactive graphics help understanding
- *Experimentation capability*
    - Large number of scenarios to consider
    - Ease of use

2.2.1 Modelling approaches

As much of the emphasis of this research relates to assessment, the following looks at modelling approaches that could be applied in this process.

2.2.1.1 Geometric modelling

This gives three dimensional representations of an object or groups of objects. Methods have been developed to represent geometry of a collection of lines and curves (wire frame), surfaces and solids in space.

- *Wire frame modelling* represents the geometric edges of an object as a combination of lines, arcs and splines arranged in three dimensional spaces. For complex objects, the amount of information that the model contains is as likely to give confusion as of clarification (Medland and Burnett, 1986).
- *Surface modelling* represents the boundaries of an object and forms surface meshes between these boundaries. There are a range of meshes or surface entities available and it is important to select the correct one for the particular application. Some common entities include plane surfaces, Bezier surface and B-spline surfaces (Zied, 1991)
- *Solid modelling* is the representation of an object as a solid (a space totally bounded by a surface) there are two methods for methods for constructing solids; boundary representation (B-rep) and construction solids geometry (CSG). The former generates a solid by sweeping model space with either a line or a wire frame about a particular axis and retains the enclosed space as a solid. The latter approach generates a solid from primitive solids which are combined using Boolean operators to achieve the desired form (McMahon and Browne, 1998).

2.2.1.2 Parametric Modelling

Parametric modelling (Ullman, 1992) describes an object in terms of parameters and constraints. The goal is to assign values to parameters so that no constraint is violated and all design requirements are satisfied. Here the design requirements are transformed from functional descriptors into geometric, physical or other parameters which pertain to the component(s). In parametric design, the design state space or solution space is determined by the number of parameter (degrees of freedom) which the designer may vary.

2.2.1.3 Constraint-based modelling

Constraint modelling is defined by Bahler *et al,* (1990) as a formalisation that represents mutually constraining parameters and their relations as a network of inter-relating constraints. Constraint modelling techniques for design aim to represent what is to be achieved, typically performance and functional requirements, rather than how it is to be achieved, in terms of process, which parametric modelling will typically implement Medland (1992). These goals are represented as constraint rules between design parameters which may be assessed at any stage in the process. The aim is to find a solution that satisfies all imposed constraints. The solution space is the intersection of all the individual constraint set (cf. figure 2.2). Such space shows all the possible solutions as well as those solutions that fail. For many constraint modelling environments this intersection is determined by optimization techniques (Thornton, 1996), which minimise the error for a given set of constraints and converges on a successful solution or the best compromise. In this manner a constraint approach allows changes in both the proposed solution and in the constraints. The former though an optimization approach and the latter by changing the strategy.

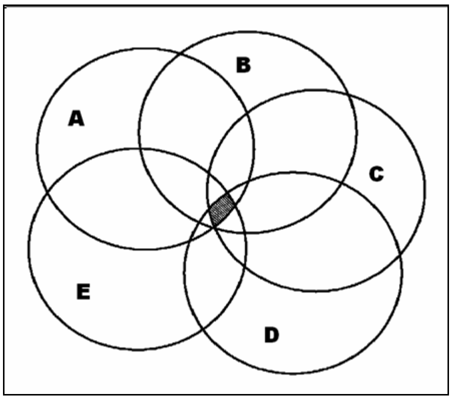


Figure 2.2 Overlapping sets form constraints (Matthews et al 2006a)

2.2.1.4 Performance and simulation modelling

Performance modelling and simulation deal with the representation of performance, where performance represents the capability to satisfactorily complete a specified task. These approaches truncate the conceptual; and embodiment phases of the design process and aim to support the designer in rapidly embodying and testing various solutions. The embodiment determines a set of parameters for the system elements which meet the desired performance characteristics for the design. For mechanical systems, this performance may well be measured at a system level, but consideration of performance for assemblies and components must also be undertaken in order to design, select and procure individual components.

2.2.2 Automated and software approaches

In order to perform investigations, assessment and evaluation of any design which have been produced, a modelling and analysis platform is needed. The following section describes existing platforms which facilitate the needs of the proposed research project. Advancements in commercial design software now allow the designer to integrate empirical data into the design model. Increased computational power now allows designers to analyze, model and simulate mechanisms and motions. Simulation such as Woolfson and Pert (1999); Gould and Tobochnik (1996) often utilizes standard packages for design though simulation approach. It generally aims to assess the performance capabilities of a particular configuration during its operation cycle. Commercial software packages (PTC's *ProEngineer* and Unigraphics NX3) allow the designer to model and perform rudimentary motion analysis (kinematics and dynamic), and component interaction. Many design packages utilizes abilities to produce parametric models PTC's *Pro-engineer* 'behavioural modelling' allows the designer to assess model sensitivity to understand the effects of change on design objectives and to Integrate results with external applications such as Microsoft Excel via an open environment. *The Pro-mechanica Motion* is a computer software tool that supports design and analysis of mechanisms from with the *Pro-engineer* environment. It gives the designer the option to check if components of the mechanism align and move as intended and also to see if they collide under motion. It allows analysis of kinematic properties. It also allows the designer to see how much torque or force is required to move the mechanism and, what are the reaction loads, generated on a connection (or joint) between components during motion.

Other packages such as *MSC Adams* give the engineer an interactive motion simulation to investigate, mechanical, pneumatic, hydraulics, electronic systems as well as what forces noise, vibrations, and harshness. *MSCDynamic* Designer Motion adds to Solidedge's Simply Motion's capabilities by allowing designs with more complicated features such as cams, gears, latches, and contact to be assessed. In addition to animation and moving interference detection, basic performance information such as linear and angular displacements, part velocities, and accelerations can be assessed graphically and through XY plots. The abilities of such systems was presented by Ning *et al,* (2005), who utilised MSC to carry out multi-body system simulation on the wheel loader mechanism of a digger.

In addition to these, higher level CAE packages such as *Boss Quattro, Noesis* and *Catia V5*, offer the engineer the option to explore the design space by implementing parametric studies. They also permit sensitivity analysis, allowing the engineer to compare the effects of several parameters on given responses. Such packages give the engineer the option to optimize selected the effects of parameter change by combining design of experiments methods. *SWORDS* (Mullineux, 2001) is a constraint modelling environment. It is primarily an academic research tool, although it has a commercial version of the constraint modelling software available from INBIS. The software functions by allowing the designer to specify constraints in terms of the design parameters. The effects of these constraints are investigated, and 'best compromise' solutions sought when the constraints are in conflict. In these cases the software uses optimisation techniques: Powell (Powell, 1978) or Hooke and Jeeves (Walsh, 1975) with or without random starts. Hicks *et al,* (2001) described a methodology using the SWORDS environment for supporting and analyzing the design of packaging machinery at the embodiment stage. This method showed the ability of the modelling package to analyze the design of a mechanism. Hicks *et al,* (2003) continued this approach into optimal redesign of packaging machinery. Barton and Lee (2002) created a framework for the modelling, simulation and optimization of hybrid systems.

Many software packages have been initially designed purely for control or analysis, such system have developed to offer system simulation as well as there original purpose. National Instruments (NI) *LabView* was originally designed as a control system for NI hardware, power supplies and test systems etc. The software has had toolkits added to perform other function. The *LabVIEW*, *NI-SoftMotion's* has also been amalgamated with SolidWorks *COSMOSMotion* to give a control development environment. The system can be used to simulate complex electromechanical systems. This system uses the 3D drafting capabilities of the CAD system and combines it with the analytic and sequencing abilities of *LabVIEW*. Control logic and analytical functions are developed in the *LabVIEW* environment from libraries. The software allows use of functions in the form of blocks from the library to produce a control chart. The two systems are view separately by the user and offer a closed loop control.

The mathematical analysis package by MathWorks, *MATLAB* incorporates the *Simulink* toolbox which is designed for modelling/simulating, controlling and analyzing dynamic motions of systems. For visual representations, solids element can be produced via plots and convex hulls, or the *MATLAB* virtual toolbox can be employed to produce animations. Analysis of the simulation is performed by the embedded *MATLAB* functions. The *Simulink* report generator extracts design information in models into technical documents. 'Body sensors' attached to points on a simulated system can be used to return its kinematic properties. Control and analysis functions are constructed from a library. These functions are placed into a *Simulink* window as block functions. These can be connected and associated with one another. The system can simulate open and closed loop systems. *LinkageDesigner* is a *Mathematica* application package developed for virtual prototyping of linkages. In the software, kinematic structures are represented by graphs, where the links are the vertices and the joints are the edges. This graph is called the kinematic graph of the linkage. To define a linkage, the kinematic pairs have to be enumerated. The software is capable of calculating the velocity, angular velocity, acceleration, angular acceleration or even higher order derivatives of any links in closed form.

The simulation and modelling approaches identified previously, all perform well in describing the physical geometrical extremes and configuration space of the mechanism and/ or machine. They offer the user the ability to analyze motion and to explore the design space of a given system. If individual analysis tools and methods are employed for detailed investigation of a particular machine or mechanism, then the ability to generate optimum or best-performing design solution is severely frustrated. With the tools and methods reviewed there are fundamental limitations, because: they allow no consideration for other modes of failure or limits; the user is constrained by the functions offered by the respective system for modelling and simulation attributes and even through, the user has modelled the design, the tool many not allow complete access to underlying constraints, which are fundamental to this approach. With these factors in mind, it is evident that there is currently no approach to answer the specific industrial question posed in this thesis. Further research into this area is required to establish an approach where the whole performance of a system can be define and analyzed to assess its ability to handle change.

2.3. POSITIONAL LIMITS AND WORKSPACES

This section describes various methodologies used define the geometric, functional and positional limits of various machines and mechanisms. The section starts with positional limits of mechanism, then describes methods for calculating the workspace of machines and mechanisms and describes some approaches used in other engineering domains to find the functional limits of systems. The section concludes with a summary of the approaches and there limitation in respect to answering the research question posed in chapter 1.

2.3.1 Positions of mechanisms and their limits

Mechanisms are used to convert between one type of motion and another. Any machine can be looked on as a group of interconnected mechanisms which convert one type of motion to a variety of other motions. The terms 'stationary configuration', 'dead centre', 'change point' and 'limit position' all mean the same i.e. when a mechanism is no longer converting motion. These generally occur when the mechanism is at the extremes of motion.

$$L \sin \Phi = R \sin \theta$$

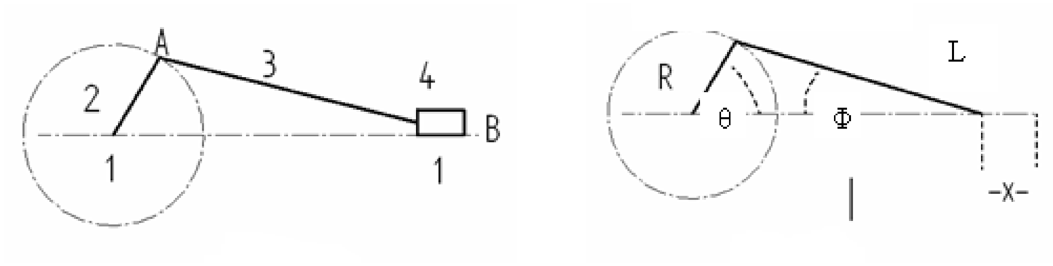


Figure 2.3 Slider crank representation

The calculation of position and kinematic limits has been well documented since the start of the industrial revolution Freudenstein (1955, 1956), Rosenauer (1956) as the three examples below shows. The calculations for determining the displacement and kinematic properties, of the slider crank mechanism shown in figure 2.3.

2.3.1.1. Displacement.

$$x = R + L - \cos\theta - L\cos\phi$$

$$x = R(1-\cos\theta) + L(1-\cos\phi)$$

$$x = R(1-\cos\theta) + L\left[1-\sqrt{1-(\frac{R^2}{L^2}\sin^2\theta)}\right]$$

It is generally sufficient to use the first two terms.

$$\sqrt{1-\left(\frac{R}{L}\right)^2\sin^2\theta} = 1-\frac{1}{2}\left(\frac{R}{L}\right)^2\sin^2\theta.............(Approx)$$

$$x = R(1-\cos\theta) + \frac{R^2}{2L}\sin^2\theta$$

2.3.1.2. Kinematics

$$V = \frac{dx}{dt} = R\omega\left[\sin\theta + \frac{R}{2L}\sin\theta\right]$$

$$A = \frac{d^2x}{dt^2} = R\omega^2\left[\cos\theta + \frac{R}{L}\cos 2\theta\right]$$

2.3.2 Workspace calculation

Previous research undertaken for the robotics industry forms a method of understanding the limits of reach and motion for robots and manipulator mechanisms. An area can be defined which represents to maximum motion for the device. This area is defined as the workspace. Much of the research into robot and manipulator workspaces was initiated in the early

1980's. The techniques for evaluating and assessing workspace limits and bounds can be sub-divided into two areas:

1. *Extended chains method* which compute the workspace by extending the manipulator in selected directions,
2. *Iterative methods* which compute the workspace by moving each joint sequentially between joint limits.

In addition there are also four common methods for determining workspaces, these are.

i. *The dextrous workspace*, (Agrawal, 2001) which is the region which can be reached by the end effector with any orientation of the manipulator.
ii. *The maximal workspace* (Meret, 1995) is defined as the region which the reference point can reach with at least one orientation.
iii. *The constant orientation workspace (*Clarke, 1976) is defined as the region which can be reached by the reference point, when the moving platform has a constant orientation.
iv. *The total orientation workspace,* (Meret, 1995) is the region which can be reached by point with every orientation of the platform in a given range.

Pusey *et al,* (2003) studied the design and workspace of a 6–6 cable-suspended parallel robot. They characterized the workspace volume as the set of points which the centroid of the moving platform can reach with tensions in all suspension cables at a constant orientation. They tried variations of the workspace volume and the accuracy of the robot using different geometric configurations, different sizes and orientations of the moving platform. The results are used for design analysis of the cable-robot for a specific motion of the moving platform. Kazerounian *et al,* (1982) developed an algorithm that plotted clouds of points to represent the workspace boundaries. These defined the cloud boundaries and are connected together to give the real workspace. Botturi *et al*, (2003) devised a general method for workspace computation based on geometric sweep of spatial elements, representing a sequence of partial workspaces. Each workspace is generated by iteratively rotating or translating the previous workspace with respect to joint axis (i) between the joint limits. Their approach achieves better workspace representation than methods such as cloud plotting method of Kazerounian *et al,* (1982), as it generates the analytical representation of all boundary surfaces. They proved their algorithm on a surgical manipulator.

Merlet *et al,* (1995) extended geometric algorithms developed by Gosselin *et al,* (1992) defining the geometric boundary edges of dexterous, total orientation, maximal and fixed orientation workspaces by only considering the limits of the actuators. Lin *et al* (2001) presented a geometrical method for the constant-orientation workspace of a hexa-slide manipulator. They defined kinematics chains for the individual elements of the manipulator e.g. leg length, platform and range of base joints. Vertex space constructions were then produced for these. These individual spaces were then considered together. This volume of the combination of the individual vertex spaces becomes the vertex space for the constant-orientation workspace. Merlet (1998) also developed an algorithm to reverse design a Gough platform from knowing the workspace. The algorithm enables users to compute all the possible locations of the attachment points of the robots whose workspace contains a desired workspace. This desired workspace is described by a set of geometric objects, limited here to points, segments and spheres, describing the location of the centre of the moving platform, the orientation of the platform being kept constant for each given object. This algorithm takes into account the leg length limits, the mechanical limits on the passive joints and interference between links.

2.3.3 Other limit analysis approaches

The following sub-section, presents the approaches that other engineering domains; structural, aerospace and automotive, electric and electronic have employed to investigate the limit states of there respective systems.

2.3.3.1 Structural engineering

The concept of understanding where the limit of a design is situated is applied in many of the engineering sub-fields. *Plastic limit analysis* or *limit state analysis* is the field concerned with calculation of the maximum load sustainable by structures which may be assumed. This approach is used in modelling new structural developments such as bridges and super structures. The theory of *limit state analysis* is the determination of a collapse load factor. In the lower bound formulation, the collapse load factor, or the load factor can be defined as a multiplying factor by which the external loads have to be multiplied in order that the structural system reaches collapse. Similarly, in the upper bound formulation, the load factor is defined as a multiplying factor by which the external work has to be multiplied in order that the structural system reaches collapse. Formally, the lower bound (or static) and the upper bound (kinematic) theorems stated Chen (1975).

2.3.3.2 Aerospace and automotive manufacturing

The trends in automotive and aerospace manufacturing are towards reduced time-to-market and quicker set up times. Industries are shifting away from dedicated transfer lines that can support highly specific high speed processes. The machining systems for these industries are likely to be four and five axis. The commercial pressures have forced manufacturers to look at virtual modelling of the process, to assess the given limitations of the process and the manufacturing equipment. MIT have developed the system of Machine Variance Analysis (MVA) (MIT, 1997). This system models the process as two chains of rigid bodies. The first chain locates the work piece; the second locates the cutting tool. MVA then animates this model, stepping through all the motions required to manufacture a specific part. MVA uses fundamentally new algorithms to precisely compute the swept envelope of the cutting tool as it moves with respect to the work piece. Thus it can determine the exact part shape even for complicated tool paths of five axis machines.

Shabaka and ElMaraghy (2005) in their investigation of reconfigurable manufacturing systems developed a system of mapping a part and building a kinemetic model of the machine system to assess the limitations of the process. The system was designed to investigate the machine axis requirement while producing parts. Commercial computer aided manufacturing systems such as Delcam Powermill5, have the facility to simulate the machining process for a given machine (Delcam, 2005). Such simulations allow the user to access the workspace of cutting tool and spindle arrangement within the working environment. Users can model the working limits of the system virtually before committing a component to the work environment and investigating the possibility of clashes with clamping or the system reaching its drive limits. Hassu (1999) developed a graphical interface "BONK" for the preparation and analysis using Bond graphs (Thoma, 1990), to simplify the analysis of dynamic systems. Bond-graphs are descriptions of systems. The structure is decreased as an assembly of connected simple elements with each element having a characteristic effort and flow variable. Bonds between the elements represent the flow of power between elements. The system was developed for use in the automotive industry, and was employed to test the dynamics of suspension systems.

2.3.3 Discussion

All the approaches described perform well in describing the physical geometrical extremes of motion for given systems and could be used to assess the system's ability to physically handle product variation. However these methods are fundamentally limited where other modes of failure or limits are considered. These could be kinematics, such as jerk; importantly none of the aforementioned methods identify interactions of individual elements while the system is in motion. Extending this though if a mechanism is modified, it would become difficult to elicit information about the new system. The workspace methodologies and their variants discussed above function well, in describing the physical geometrical extremes of motion for given systems and could be used to assess the systems physical ability to handle product variation. Modification of these methodologies could be used to assess the ability of the mechanisms to handle functions for which they were not originally designed. However research into this area is required to define a methodology where the whole performance of a system can be define and analysed to assess its ability to handle change

2.4 GRAPHICAL REPRESENTATIONS OF MULTI-VARIBLE PERFORMANCE DATA.

Previous sections have shown the variety of design, modelling, simulation and analysis options that are available to the engineer. It is often stated that "a picture paints a thousand words". This is true when generated data is presented in graphical form. It offers the engineer the enhanced visualization of the problem. The problems stated in chapter 1, are no different. For this reason another factor that has to be taken into account is: how to graphically represent any data generated by an applied design approach. This section gives a flavour of some of the options available and presents their limitations.

2.4.1 Graphical techniques

Graphical representations defined in this section are visual portrayals of the quantitative data. Campbell *et al* (1983) have defined two fundamental classes. Those displaying the data themselves, these are generally used when exploring data. The other, displays quantities derived from the data. This type is used to enhance statistical analysis, and is based on assumptions about relationships in the data. Two and three dimensional data can easily be presented using conventional tools such as histogram.

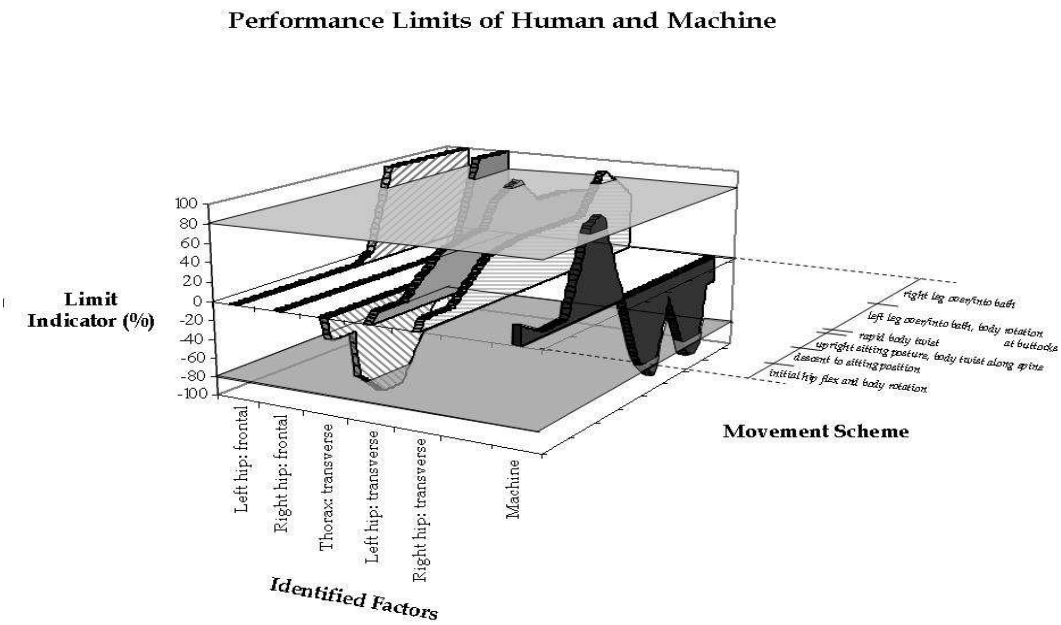


Figure 2.4 Performance limit area plot(Mitchell et al 2003)

Mitchell *et al,* (2003) whose work investigated the sit to stand motion of people, used area plots to represent the performance limits of motion for a person (cf. figure 2.4). However many applications in science and engineering have a greater number of variables than three, which raises other representation issues. Feiner and Beshers (1990) describe how such data has to be defined by points in Euclidean *n-space*. A point's position is then specified with *n* co-ordinates, each of which determines its position relative to one of *n* mutual axes. The approach was to develop an architecture where *n*-dimensional data could be nested within related data. "worlds within worlds". Other approaches are described in the following sections.

2.4.1.1 Cloud map

A cloud map is a multi-dimensional scatter gram / scatter plot. It is a powerful graphic tool for displaying multi-variable data. It is predominately a statistical tool which is employed across many fields., such as Hocking(2001) in the study of geophysical data (figure 2.5) or in the health research with examples such as Sosnowski *et al* (2001) employed variant patterns of scatter plot of short-term heart rate variability and Buhimschi *et al,* (2002). In comparison of inner womb pressure (Intrauterine pressure IP) against bearing down (Valsalva) movements, the author's hypothesis was "That delivery is faster if women are instructed to voluntarily bear down in synchrony with their uterine contractions". Although points plotted in such a way as these two examples can have their measures of association investigated using the Pearson correlation co-efficient. There is still difficulty when interpreting these plots when the density of points in a region becomes high.

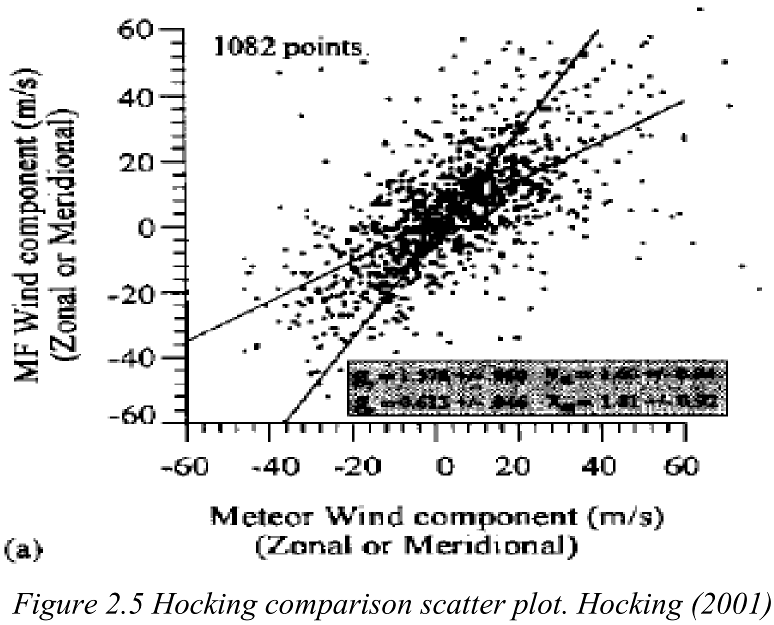


Figure 2.5 Hocking comparison scatter plot. Hocking (2001)

Cleveland and McGill (1984) developed the sunflower plot to overcome this issue. The sunflower is a number of short line segments, called petals, which radiate from a central point. The number of petals of each sunflower equals the frequency of the number of observations in the associated with that point. Sunflower plots are effective at dealing with the 'overstrike' problem that arises with high-density scatter plots (cf. figure 2.6). This work was continued by DuPont and Plummer (2003) who added density representations to the plot so points in high density areas can be identified

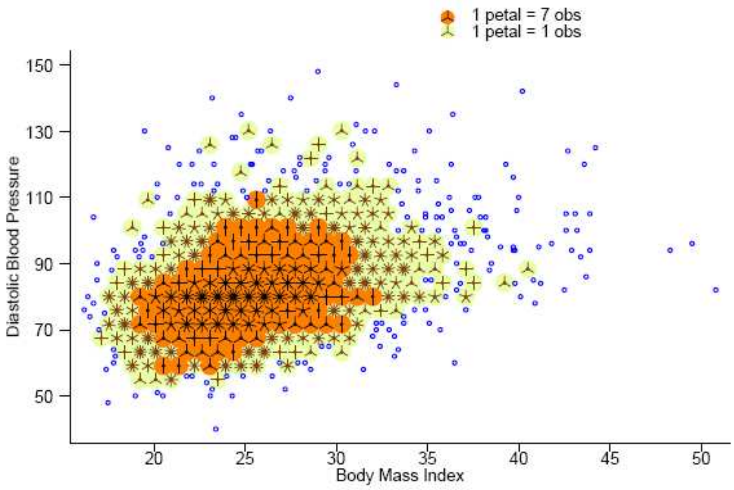


Figure 2.6 Sunflower scatter plot. (Cleveland and McGill, 1984)

Beyond the statistical visual usage of cloud maps there are other applications where they can be employed. In engineering mechanisms the cloud map has been used as a visual tool by Kazerounian, *et al,* (1982) to represent the workspace boundaries of robots. These defined cloud boundaries are connected together to give the real workspace. Kosara *et al,* (2004) used scatter plots as a tool for linking scientific and information visualizations. In their paper they showed the example of a catalytic converter made up 19600 dimensions relating to factors such as velocity vectors and pressure etc. Using linking and brushing techniques, the dimensions can be shown with colour variation in the parameter space. Kosara *et al* . work highlights the use of interactive three dimensional scatter plots in presenting functionality of a system. Another approach to presenting data of more than three dimensions is to lock variables to one another. This way individual variables can be plotted/ investigated.

An extension to the Scatterplot is the Scatterplot-matrix (Carr *et al,* 1987). This is a rectangular array of scatter plots. Instead of numeric values, such as the correlation coefficient, each element of the matrix is an individual scatter plot. This is useful for visualizing how a dataset is distributed through multiple variables. By symbolizing all of the scatterplots in the matrix the same way, you can see how the same clusters of points change shape from one scatterplot to another. Using this technique, hundred's of plots can be scanned quickly and easily.

2.4.1.2 Convex hull

In the field of mathematics, the convex hull for an object or a set of objects is the minimal convex set containing the given objects (Shamos and Preperata, 1985). Vidmar and Pohar (2005) support the idea of convex hull's to replace the cluttered scatter gram diagram. They use the space gained by the production of the convex hull for statistical error bar and confidence ellipses. They emphasise the convex hull as a suitable replacement for scatter grams if the data groups are large and have considerable overlap of points. Their work concentrated on two dimensional plots and they presented biomedical examples (i) gender differences in age at death and paid personal income, (ii) an augmented bi-variant density plot of standardized score of the days with patient-reported bleeding in relation to 'conization' techniques. Using the convex hull as a boundary tool is only an approximation. (cf. figure 2.7).

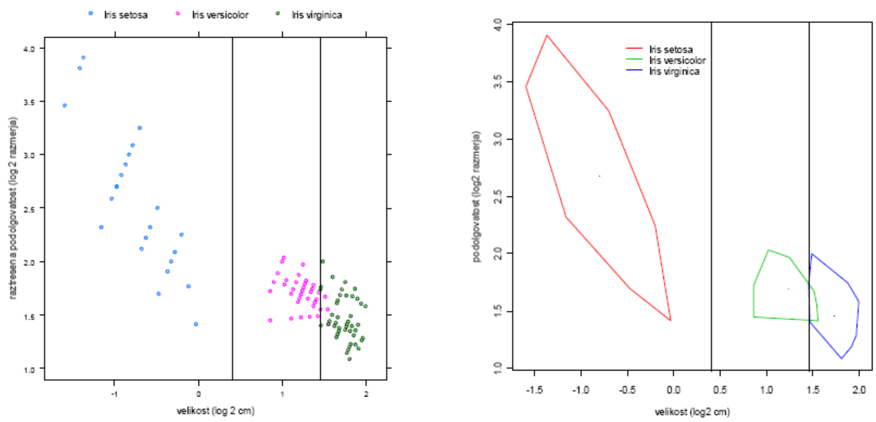


Figure 2.7 Example convex hull used in Vidmar and Pohar(2005)

2.4.1.3 Box plots

The box plot (Tukey, 1977) is a statistical comparison tool. It is predominately used to present location and variation information in data sets. Parmee (2004) promotes the idea of employing parallel co-ordinate box plots representations as a “central depository” for containing relevant and multi-objective information. A combination of box plots representation and parallel coordinates is shown by figure 2.8. The parallel co-ordinate representation displays the variables vertically next to each other.

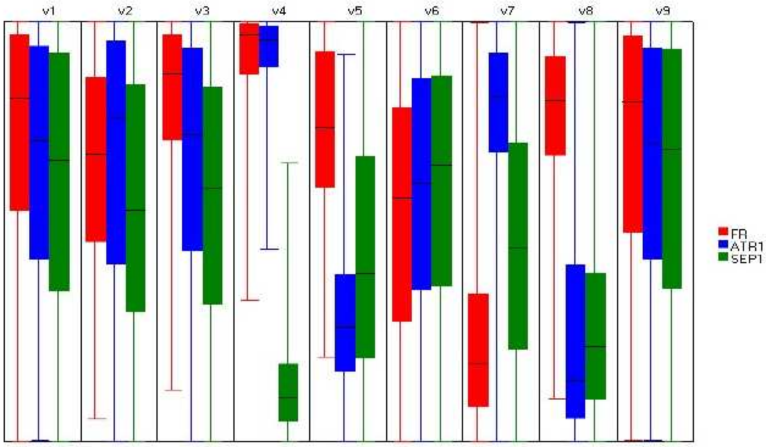
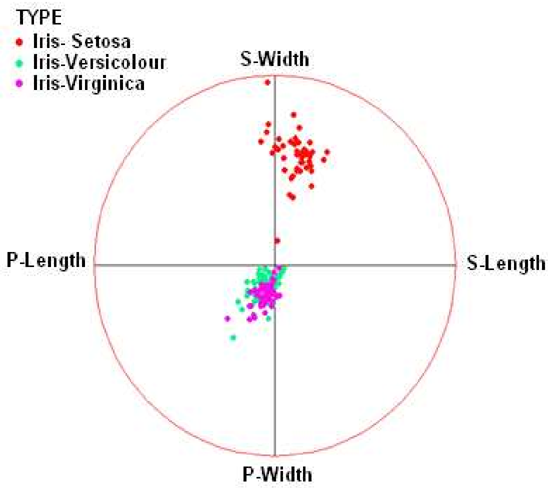


Figure 2.8 Parallel box plot diagram Parmee (2004)

2.4.1.4 RadViz and PolyViz

RadViz (cf. figure 2.9) is a display technique that places dimensional anchors (dimensions) around the perimeter of a circle (Hoffman and Grienstein, 1999). Spring constants are utilized to represent relational values among points - one end of a spring is attached to a dimensional anchor, the other is attached to a data point. The values of each dimension are usually normalized to the 0 to1 range. Each data point is displayed at the point where the sum of all spring forces equals zero. The position of a data point depends largely on the arrangement of dimensions around the circle.

The PolyViz (cf. figure 2.10) visualization extends the RadViz method with each of the dimensions anchored as a line not just a point. Spring constants are utilized along the dimensional anchor (the line) that corresponds to all the values the dimension has. Each data point is positioned as in RadViz. The position of the point in the display depends as in RadViz on the arrangement of the dimensions. PolyViz provides more information than RadViz by giving insight into the distribution of the data for each dimension.



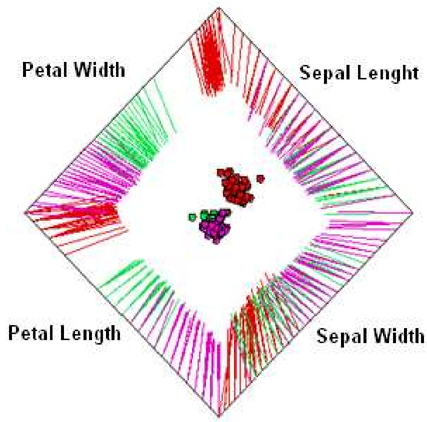


Figure 2.9 RadViz plot *Figure 2.10 PolyViz plot*

2.4.1.5 Concurrency plots

Nomography deals with the graphical representation and solution of mathematical relations that are either explicit or implicit. Steinhaus (1983). nomographs are quick to generate visual representation of the interrelationship between variables. A concurrency plot is a nonograph that presents in a Cartesian co-ordinate system, the graphical solution of a relation among three or more variables Levens (1968). As an example of its use we, can consider the following example,

$$a + b + c = d \qquad (2.1)$$

The example can easily be replaced by two equations.

$$a + b = T \qquad (2.2)$$

$$T + c = d \qquad (2.3)$$

Which are both straight lines, Figures 2.11, 2.12 show examples of these for the values of b and c. these can be combined to produce the concurrency figure 2.13.

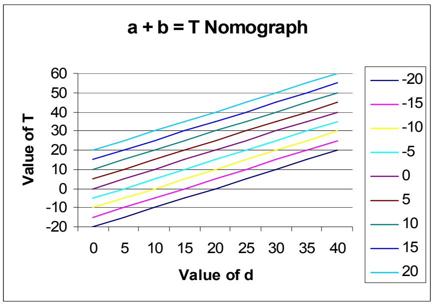


Figure 2.11 a+b+T Nomograph

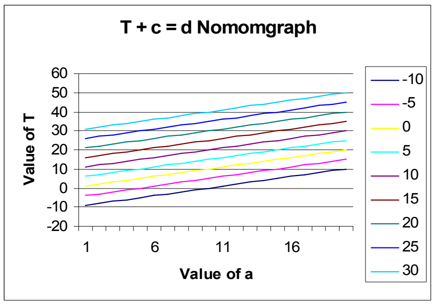


Figure 2.12 T+c=d Nomograph

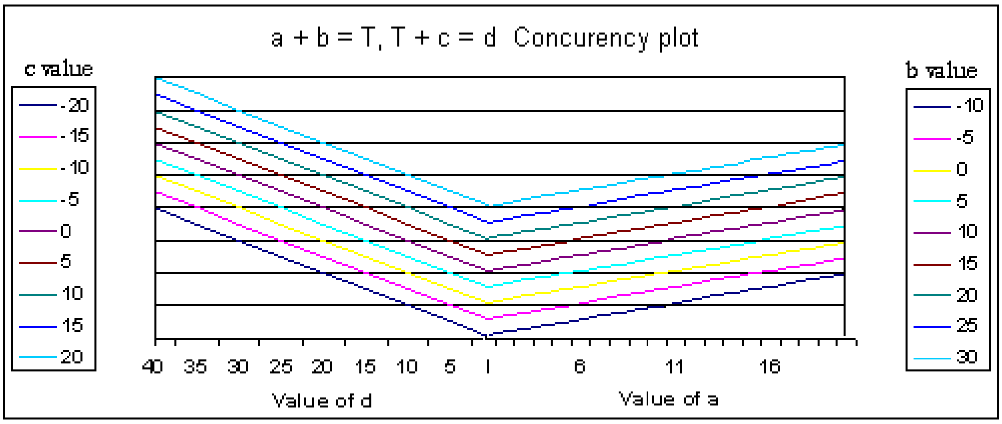


Figure 2.13 a+b+c=d solution concurrency plot

2.4.1.5 Nested performance charts

Figure 2.14 shows an example of a nested design chart (Burgess *et al* 2004*)* for the structural design example considered in this paper. The discrete variables are H_l and H_r and these are considered at three discrete values. The variables α and θ are plotted on traditional two-variable performance charts within each box of the matrix. In the top right-hand corner of each sub-chart a ranking is given from first to ninth that ranks the peak performance within each chart. First represents a peak performance with the lowest weight structure. The figure also shows a path from the worst peak performance to the best peak performance.

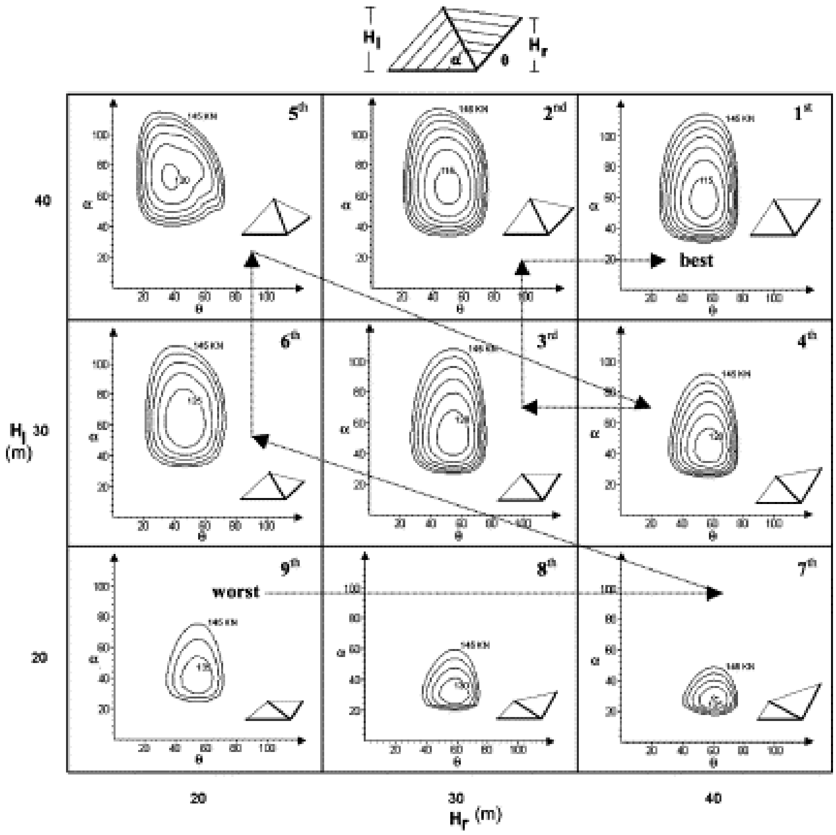


Figure 2.14 Nested performance chart (Bugess *et al* 2004*)*

2.4.1.6 Graphic representation discussion

As noted by Feiner and Breshers (1990), up to and including three dimensions the presentation of data is simple. The methods for more than three dimensions are difficult. Locking three plus data to three variables allows more than the results to be produced but this can result in loss of clarity of representation. It can be seen that several visualizations deal with high dimensions quite well. These include RadViz and PolyViz. The approach used by Feiner and Breshers (1990), in embedded respective data *'worlds within worlds'* give the same problem as locking data but also requires a software architecture to embed and extract the data. While others approaches like the box plot by Parmee (2004), multi-scatter plots (Carr *et al, 1987)* and nested performance (Bugess *et al,* 2004*)* only gives a representation of an instance in time for a scenario against maximum and minimum values for the variables, and require multiple plots for investigation. One aspect of the goals of this thesis is to find a representation technique where the performance and function of a system can be plotted along with some kind of visualization of the area of mechanism failure for a variant product.

2.5 Conclusion

The chapter has reviewed the state-of-the-art for four subject areas which relate to the search for a solution to the problem stated in chapter 1. These areas have been: engineering design, modelling and simulation, workspace and performance analysis and multi-variable representation techniques.

- For *engineering design* it was highlighted that the basic theories all have one factor in common, specifically that design is a problem solving activity, and they just offer knowledge of the design process. It was shown that machine design is an active research area, firstly for the underlying mechanisms and secondly for the development and evolution of system to accommodate product variety, the latter is an important area which is spawning much new research.
- The *simulation and modelling* approaches identified above perform well in describing the physical geometrical extremes and configuration space of the mechanism and/ or machine. They offer the user the ability to analyze motion and to explore the design space of a given system. If individual analysis tools and methods are employed for detailed investigation of a particular machine or mechanism, then the ability to generate optimum or best-performing design solution is severely limited. With the tools and methods reviewed there are fundamental limitations, because:
    - They allow no consideration for other modes of failure or limits.
    - The user is constrained by the functions offered by the respective system for modelling and simulation attributes.
    - Even through, the user has modelled the design, the tool may not allow complete access to underlying constraints, which are fundamental to this approach.
- With the existing techniques for finding limits, all the approaches described perform well within their own domains for describing the physical geometrical extremes of motion for

given systems and could be used to assess the system's ability to physically handle product variation. However these methods are fundamentally limited where other modes of failure or limits are considered. These could be kinematics, such as jerk; importantly none of the aforementioned methods identify interactions of individual elements while the system is in motion. Extending this though if a mechanism is modified, it would become difficult to elicit information about the new system. The *workspace methodologies* and their variants discussed above function well, in describing the physical geometrical extremes of motion for given systems and could be used to assess the systems physical ability to handle product variation. Although modification of these methodologies could be used to assess the ability of the mechanisms to handle functions for which they were not originally designed. Further research into this area is required to define a methodology where the whole performance of a system can be define and analysed to assess its ability to handle change

- For results visualization, prior research has shown that, up to and including three dimensions the presentation of data is simple Feiner and Breshers (1990). The methods for more than three dimensions are difficult. Locking three plus data to three variables allows more than the results to be produced but this can result in loss of clarity of representation. The approach used by Feiner and Breshers (1990), in embedded respective data 'worlds within worlds' give the same problem as locking data but also requires a software architecture to embed and extract the data. Other techniques such as Box plot, multiple scatter plots and nested performance plots, all reply on the plotting of multiple instances of the results data set for analysis and investigation. No existing dedicated representation technique exists where the performance and function of a system can be plotted along with some kind of visualization of the area of mechanism failure for a variant product

This chapter has shown that there is currently no approach to answer the specific industrial question posed in this thesis. What is needed is a methodology where the whole performance of a system can be defined and analyzed to assess its ability to handle change.

Chapter 3

Previous constraint-based implementations

"The more constraints one imposes, the more one frees one self"
Igor Stravinsky

In proposing a solution to the problem introduced in chapter 1, a constraint-based approach has been advocated. To this end, it is important to present how engineering domains have used constraints and their effectiveness in helping to search for the solution to engineering problems. This section aims to show the vast array of constraint-based approaches: constraint rules or types, and the variables styles that have been implemented successfully in solving and assessing an array of engineering problems across the whole product lifecycle (PLC). It is important to consider the whole PLC to identify any approaches that have been employed for assessment. The work presented here fulfils objective 2 from the introduction chapter.

As the research presented in this thesis spans both design and manufacturing domains, this chapter is divided into sections under these headings. Details of approaches employed are presented and appraised in the discussion at the start of each sub-section. This is supported by two comparative tables showing the types of constraint rules used and the areas of application. It also highlights the variety of constraint techniques used: constraint satisfaction, optimization and checking/ monitoring. This is vital to understanding which technique is most appropriate for assessment problems This chapter not only provides an appraisal of any previous research in the problem area off thesis, it also presents the constraints from the design and manufacturing domain that this thesis must consider. This chapter concludes by identifies the areas in the product lifecycle where constraint-based techniques have not been employed or fully exploited.

3.1 CONSTRAINT HANDLING OVERVIEW

Although the research presented in this thesis is not directly concerned with the techniques used to handle the constraints. In reviewing previous work, much emphasis has been placed on these techniques over the problem content. This section further elaborates on this. There is a multitude of heuristic algorithm employed to resolve and investigate constraints. These include direct search Lewis *et al,* (2000), approximation techniques, enumeration procedures, branch and bound, relaxation, local search algorithms like simulated annealing, Tabu search, and evolutionary algorithms (Deb, 2001) which have developed from analogies of the works of Charles Darwin and his theories of natural selection and preservation of favoured race in the life struggle. Examples of which are genetic algorithms, particle swarm optimization and ant colony optimisation. An evolution of approaches is that of meta-heuristics, this is a top-level general strategy which guides other heuristics to search for feasible solutions in domains where the task is hard (Kumar, 1992). Further descriptions of such approaches are shown in appendix c.

3.2 CONSTRAINT IN DESIGN

The importance of constraints has previously been discussed, in the design activities Suh (1980), Ullman (1997) and Pahl and Beitz (1996), and is the basis of the approach presented by Gross (1986, 87) for the early stages of architectural design. Thornton (1996), states that the core element of the design process is the recognition, formulation, satisfaction and optimization of constraints which are constantly added removed and modified in an iterative fashion. A common factor to all major design theories identified in chapter 2 is, at the planning and clarification stage, a major element is the identification of task-specific constraints for the design. And the understanding of which constraints are essential and which are ‘fictitious’ e.g. whether, because a company has always pneumatic actuators for product translation, that for a new design, the designer must be constrained only to using pneumatics. It is the knowledge of the design constraints that guides the designer to find a solution. The constraint-based approaches for four key elements of design are investigated in this section: conceptual design, embodiment of design, detailed design and upgrade and conversion of design.

3.2.1. Conceptual design stage

Conceptual design is regarded as the phase of the design process in which the design engineer takes a specification for a product and generates many broad solutions to it (O'Sullivan, 2002). Mullineux *et al,* (2005) describe how a constraint modelling environment can be used to aid the early stages of the design activity by searching for solution principles and evaluating these principles against the constraint rules. Deng *et al,* (2000) proposed a generic constraint-based functional design verification model. The verification is achieved by identifying the input and outputs design variables, and employing a variable dependency graph (network), to allow the user to propagate and check the variables against the constraints. Gross (1986, 1987) presents an approach using the 'constraint explorer', a computational environment for designing based solely on constraint descriptions. The author explored the region of alternatives designs by trying different values for variables and comparing the results. The system covers the making of decisions, exercising preferences, exploring possibilities, choosing among alternatives, and backtracking. This illustrated the implementation of the explorer with examples from the design of the built environment.

O'Sullivan (2002a, 2002b) presents an interactive constraint-based approach to supporting the designer at the conceptual design stage. He proposes a computational reasoning environment based on constraint filtering as the basis of an interactive conceptual design support tool. Utilising this tool, the designer can be assisted in developing and evaluating a set of schemes that satisfy the various constraints imposed on the design. The tool allows modelling to be performed and some reasoning about the design of products from a defined set of requirements. The approach presented by O'Sullivan not only addresses the issue of modelling and reasoning about the design of products from an abstract set of requirements, but it also demonstrates how life-cycle knowledge can be incorporated into the conceptual design of a product and how alternative schemes can be compared.

Holland *et al* (2004) have developed an add-on constraint based design technology for Autodesk inventor. Their system divides the process into three sections.

- *Design specification*: where customer needs define the functionality and physical specification.
- *Conceptual design knowledge*: here they use a 'function-means map'. The means for this system are design principles and design entities. The relationships of the functions employed describe how the parts in the scheme should be configured.
- *Scheme configuration*: during this embodiment process, the context relations from the design principles used the scheme will be used as a basis for defining the interfaces (constraints) between the design entities and are used to ensure the configurability of the product.

The system does not restrict the designer from taking any design path he/she wishes throughout the conceptual stage of design.

Wilhelms (2005) presents a conceptual design model, which allows the user to model to the entire conceptual design phase: desired functionality (functions); achieved functionality (means and their value choices), and explicit constraints (internal and external relations between parameters of requirements, functions and means). Five different types of constraints are used to interconnect the elements of the modelling:

- *Value assignments constraints* are used to assign a definitive value to a parameter. These value assignments are concept specific; the same means can thus have different parameter values when they occur in different concepts.
- *Requirement function coupling constraints* connects requirements and function parameters.
- *Internal constraints:* are used to describe the physical effects a means is based upon.
- *External constraints* model flow between different functions (these are added manually). Finally,
- *Identity constraints* are set automatically and model the identity of a corresponding function and means parameter. The authors applied constraints to the model quantitative relations to enable early calculations.

Brix *et al* (2003) presents the development of a feature and constraint-based model to support the early stages of product design. The conclusion of this work was presented in

Brix *et al* (2006) where the MASP (modelling and analysis of solution principles) is described. Their research demonstrates functional modelling in the conceptual design phase. It dealt with the development of high precision positioning and measuring machines and mechanisms. The tool allows the user to test the functionality of the design in respect to: static and kinematic behaviour, required space, behaviour under tolerance and disturbing influences and collisions. Research by Thornton (1996) employed a product model to store geometric variables and constraints. The model supports dimensional, geometric, positional and interference knowledge. The aim of the research was to use constraints to support the search for feasible designs solutions. In Zhang *et al,* (2000), a knowledge-based functional reasoning strategy. The reasoning process produces a chain of interconnected behaviours. Two behaviours are connected when there is compatibility between the functional output of one and the corresponding functional requirements. The connectivity satisfies all the functional constraints. In Homann and Thornton (1998) a design tool is presented to aid the design process for high precision machinery. The tool is employed to assess the machine tool based on kinematic modelling, error motions, and design constraints. The specification of constraints, errors and kinematic models is enabled through a standard library of common precision machine elements. They demonstrated their approach on a machine tool spindle.

3.2.2. Embodiment design stage

Embodiment design is the stage in the engineering design process when the solution abstracts of conceptual design take shape and are transformed into detailed design. (Pahl and Beitz,1996). Hicks *et al,* (2001) describes a methodology using a constraint modelling environment for supporting and analysing the design of packaging machinery at the embodiment stage. This method shows the ability of the modelling package to analysis the design of a mechanism. Fa *et al*, (1993) develops a constraint-based modelling system that determines the degrees of freedom of a constrained object operationally in terms of allowed rigid motions of the object. For each new constraint on the object, the allowed motions are reduced using table look-up. Feikes *et al,* (2002) proposed the use of a constraint-based approach to overcome the limitations of a mechanism based solution for calculating the displacement of a three dimensional geometric model of the knee joint (Wilson, 1996). Mechanical based solutions would not converge near the ‘stationary configuration’. The constraint based formulation allowed for the incorporation of more physiological articular surface shapes in the knee model and thus permits examination of the effects of surface shape and ligament arrangement on joint kinematics. This approach was adopted to aid knee joint replacement design

Thornton and Johnston (1993), investigated the usage of constraints and constraint satisfaction techniques in the embodiment stage of the design activity. This research was further expanded by Thurston and Johnston (1996), who developed CADET (Computer-Aided Embodiment Design Tool). The system aids the design engineer in formulating and satisfying algebraic constraints. It consists of a generic database of components that can be used to develop a constraint-based model of geometry of the product that is to be designed. The system uses simulated annealing to resolve the constraints. Nagai and Teraski (1993) developed a constraint-based knowledge compiler for parametric design in mechanical engineering called MECHANICOT. The system is based on the assumption that the design process can be modelled as a constraint satisfaction problem. The purpose of the tool is to generate design knowledge compilation techniques. It was proposed that the MECHANICOT knowledge compiler could be useful for supporting the reuse of design knowledge that could be used for producing design plans.

Hashemian and Gu (1996) employ constraint networks to model the downstream aspects of the design process (product maintenance, recycling and disposal), so that such information can be employed effectively during the embodiment design activity. The developed constraint-based system takes functional requirements of a product and other concerns about its potential life cycle and models them as constraints. There system supported constraints from multiple knowledge sources. The authors labelled the required constraints under six headings: geometric, functional, material, manufacturing, standards and marketing. Bracewell *et al* (2000) presents how object-oriented modelling and simulation offer the potential for effective constraint management in embodiment design. Used in combination with a knowledge-based system front-end, this can provide a true virtual prototyping design system with animated dynamic models of the artefacts produced. These are based on rigorous mathematical models, and are ideal for subsequent evaluation and optimization. The system has built-in constraint checking, ensuring that any instance of a virtual simulation does not violate any constraints in the design.

3.2.3. Detailed design stage

Detailed design is the process of refining and expanding the preliminary design of a system or component to the extent that the design is sufficiently complete to be implemented. Much the constraint-based work has focused on computer aided design and its software. For the detailed design stage are two types of geometric constraints: *numerical* constraints, such as distance and angle, which gives numerical information and *symbolic* constraints, such as coincidence and parallelism, which gives logical information (Fudos, 1995). In most of the commercial CAD systems available today, the process of geometry creation starts with the creation of a rough 2D sketch. The designer draws a rough sketch. There are different geometric entities available such as points, lines and circular arcs for the designer to draw a shape. There are two different ways of attaching constraints to a sketch: applied to the sketch by the designer while creating the sketch; the *constructive approach*. Alternatively the constraints may be detected by the CAD software (by evaluating a rule base). Some systems may support both approaches. The rules add 'intelligence' to the package allowing it to apply respective constraints on the assumption that this is the designer's intention. The designer then annotates the sketch with necessary dimensions and constraints (Andrl and Mendgen, 1996).

Geometric constraints include a variety of types, the most commonly used ones can be categorized as in Table 3.1. These constraints are in the form of geometric relationships on the 2D design. Geometric constraints are not mutually exclusive, which means that one constraint relation may be represented by another constraint. For example, perpendicularity can be represented as an angle of 90 degrees. Most of these geometric constraints are defined by the user. However there are some constraints that are automatically inferred by the system itself for example perpendicularity and parallelism. Again in 3D geometry creation and manipulation, constraints play a vital role. These constraints are present as relationships between the different geometric entities. These relationships can be categorised as geometric relationships, algebraic relationships and topological relationships. An example is when extruding a simple 2D circle to form a cylinder; the designer can always specify a relationship that the height should always be double of the radius of the cylinder.

Table 3.1 Geometric constraints

Dimension	Position	Orientation	Symmetry	Tolerance
Distance	Fixed	Angle	Line symmetry	Dimension
Radius	Coincidence	Horizontal	Plane symmetry	Straightness Flatness
Diameter	Concentric	Vertical		Circularity
	Point on curve	Curve parallel		Cylindricity
	Curve on surface	Surface parallel		Of a line
	Curve tangent	Collinear		Of a surface
	Surface tangent	Coplanar		Angularity
		Perpendicular		Perpendicularity
				Parallelism
				Position
				Concentricity
				Circular run-out
				Total run-out

Martinez and Felez (2005) developed a constraint-based approach for detailing designs. Their method defines the constraints and geometry of a two dimensional sketch and relates this to the complete dimensioning of the sketch. Parts are dimensioned using given drawing standards (ISO 129). This approach establishes whether the system is over or under constrained. Using their dimensioning criteria redundant constraints are highlighted. Although the system selects the most suitable dimensions, the designer also has the ability to alter dimensions and the system reconfigures and then substitutes the other dimensions. Mullineux (2001) presented a constraint-based modelling system called "SWORDS", which allows variables and geometric entities to be defined and constraints imposed upon these. An optimisation scheme is used in the resolution of these constraints. The authors show how the system is applicable to the types of problem encountered in constraint-based sketching systems, assembly modelling systems and mechanism simulation.

Andrl and Mendgen (1996) highlights how modelling with constraints supports design in iterative steps because it supports the designer to sketch new ideas very quickly by providing highly sophisticated sketching tools and to change existing features of the design by modifying existing constraints, this follows through to the detailing of drawings. This offers the design engineer the opportunity of modelling the history and topology of the features as well as modelling the constraints applied to objects. Au and Yuen (2003) extended feature based modelling for sculptured objects they develop a feature modeller to generate models from feature class constraints. These constraints were instantiated by the modelling operations during the modelling session. In feature-based CAD systems the components created are parametric and the relationships between the different geometric entities are described by the constraints. Again the models can be reconstructed by changing the parameters of the features. Constraints are used to keep the shape of these features consistent and valid. Once the different parts of a design are created the next stage is to assemble these parts.

Singh *et al* (2006) presents the benefits to assembly modelling of mechanisms by of incorporating a stand alone constraint based modeller into a commercial computer aided (CAD) design package. This gives the advantage that the constraint modeller can define the underlying geometric entities and can have subsequence access to these via pointers. In particular, it is possible for the constraint modeller to apply transforms to the CAD entities and hence take control of the assembly process. This allows the user greater interaction with the assembly and hence provides the ability to investigate arrangements

3.2.4. Upgrading and redesign/ conversion

Redesigning/ conversion and upgrading, are the processes of changing a component or system to suit some new purpose; for example to process a new product. Hicks *et al,* (2003) extend a previous approach (Hicks *et al,* 2001) into the optimal redesign of packaging systems. This approach was supported by two industrial case studies, a carton crash erection mechanism and an over wrapping machine. The approach bounds maximum and minimum kinematics properties for the given mechanism and optimises the mechanism to find the best solution. Although Brix *et al,* (2006) aimed their research for the early stages of design. They suggest that the feature and constraint based tool could support the reuse of design solution principles from different information sources and their adaptation to current requirements.

A methodology for performance envelope exploration is described in Matthews *et al* (2006b, c). The methodology was directed at machines associated with the food processing and packaging industry. Again the manipulation of design variables is employed to find a solution that satisfies presented constraint rules. At a higher level the modeller was used to associate failure modes to the model. For example, one failure mode may be the clashing of parts of the machine with each other or with the product. An interference check between solid objects within the model can be undertaken. An alternative to full interference checking is bounded boxes, where a box is a rectangular block contains an object throughout its motion. Parametric variation was employed to disturb the existing mechanism to find variant solutions for different products. Ollinger and Stahonich (2001) presented a program that generates proposals for achieving redesign goals; it identifies side effects (potential or certain) and suggests additional changes to counteract those effects. The approach is aimed at the early stages of the redesign process, aligning it usage with that of the approaches presented in section 3.1.1. Along with constraint checking the approach employs quantitative reasoning and heuristic search. The emphasis is on the production of potential redesign plans.

3.2.5 Design discussion

The following table shows a breakdown of the constraint-based approaches which have been employed for design activities. The table presents the aim and contribution of the research and the goal which the authors employed the constraints for. Within this the constraints the authors had to deal with are identified. The table also identifies the design task and the design domain into which the research fits.

Table 3.2 Constraint-based applications for design.

Author(s)	Aim /contribution	Design Task	Domain	Constraint handling	Constraints	Objective criteria / goal	Case Study
Au and Yuen (2003)	Generation of feature models from feature class constraints	Geometry	CAD/CAE	Satisfaction	Connectivity, Continuity, attachment	Shape consistency	Manikin
Andrl and Mendgen (1996)	The use of constraints in the geometric modelling process	Geometry	CAD/CAE	Satisfaction	Geometric and topological	Functioning models	Drawing
Bracewell *et al,* (2000)	OOE and simulation for embodiment stage of design	Embodiment	Mechanical systems	Checking	Design limits and physical laws	Design parameter reduction	Model aircraft engine

Feikes *et al*, (2002)	Development of constraint-based model of the knee joint	Embodiment	Human Systems	-	Correctly dimensioned drawings	Functioning model of knee joint	Human knee
Gross (1986)	Using a constraint-based approach to design architecture	Conceptual	Architectural	Satisfaction	Architectural requirement and design laws	Feasible designs	Architecture
Hashemian and Gu (1996)	Constraint network to model down-stream aspect of design	Embodiment	Mechanical systems	Satisfaction	Geometric limitations, materials and standards	Feasible designs	Hydraulic jack
Hicks *et al*,. (2001)	Design of packaging for complex motion	Redesign	Mechanical systems	Optimization	kinematics and connectivity between elements	Reduced kinematics	Packaging machines
Hicks *et al*, (2006)	Design of mechanisms for complex motion	Embodiment and optimisation	Mechanical systems	Optimization	Connectivity between geometry, system inputs/ outputs	Optimal design	High speed machinery
Hoffman and Joan-Arinyo (2005)	Constraint solving for geometries in CAD systems	Geometry	CAD/CAE	Satisfaction	Connectivity between geometry and elements	Correctly assembled geometry and models	CAD images
Honmann and Thornton (1998)	Machine error simulation and concept evaluation.	Conceptual / embodiment	Mechanical systems	Satisfaction	Geometric limitations and functional requirements	Conceptual design selection	Machine centre
Holland et al (2004)	Constraint-based design support for Autodesk inventor	Conceptual	Mechanical systems	Satisfaction	Relations between functions	Development and configuration of design	Engine components
Martinez and Felez (2005)	Detailing of drawing against ISO standards	Detailed	CAD/CAE	Optimization	Relations between geometry. Drawing standards	Correctly dimensioned drawings	CAD drawings
Matthews *et al* (2006:c)	Design of mechanisms for complex motion	Embodiment and optimisation	Mechanical systems	Satisfaction and checking	Geometry Connectivity system inputs/ outputs	Design space exploration	Food equipment
Mullineux (2001)	Using numerical optimization in drawing/ assembly	Geometry	Mechanical systems	Satisfaction	Connectivity between geometry and elements	Correctly assembled geometry and models	Mechanism and Box
Nagai and Teraski (1993)	Constraint-based knowledge compiler for parametric design problems	Embodiment	Mechanical systems	Satisfaction	Design requirements	Building knowledge-based systems for parametric design	Machine spindle head
O'Sullivan (2002a, 2002b)	Assist designer in developing and evaluating schemes	Conceptual	Mechanical systems	Satisfaction	Define relations between the functions and their means	Constraint checking	Bicycle
Singh *et al* (2006)	Design of mechanisms for complex motion	Embodiment and optimisation	Mechanical systems	Optimization	Connectivity between geometry, system inputs/ outputs	Feasible designs	Packaging machines
Ollinger and Stanhovich(2001)	Evaluation of proposed redesign plans of engineering devices	Redesign	Mechanical systems	Checking	Design requirements on quantitative	Design requirements	Diesel engine
Thurston and Johnston (1996)	Constraint-aided environment for preliminary design	Embodiment	Mechanical systems	Satisfaction	Geometry and forces	Feasible designs	–
Thornton (1996)	The use of constraint satisfaction techniques to aid design	Conceptual / embodiment	Mechanical systems	Satisfaction	Design requirements	Feasible designs	Connection rod
Wilhelms (2005)	Networks to quantitatively model evolving incomplete systems	Conceptual	Mechanical systems	Satisfaction	Function coupling, internal, external, identity	Best Quantitative solution	Hydraulic rock drill
Zhang *et al* (2002)	An intelligent K-B system for functional design	Conceptual	Mechanical systems	Satisfaction	Precision, compactness, cost, efficiency, manufacturability	Satisfaction of all the functional constraints	–

In the conceptual stages of the design process, function is of prime importance. The approaches described in this section have used constraint-based techniques to elicit and manipulate knowledge about the design concept. This has then been used to aid the design process for a variety of domains and design task. The constraint-based approaches aid the designer in the development and configuration of a design and allow the possibility to find best Quantitative solution and feasible designs. As noted in the introduction, when considering the design embodiment activities, constraint-based approaches have generally been employed to analyse both products and processes. The knowledge of the constraints that bounds the limit of performance allows the designer to develop strategies to look firstly to define what the existing performance of the design is. It allows the ability to search for potential optimal solutions to the design performance.

The use of constraints has also enabled users to overcome the fundamental limitations of analysis with purely mathematical approaches. The detailed design section shows that constraints within geometry present specific relationship knowledge such as: the distance between two geometric entities, angle, incidence and tangency). Most of these constraints are defined by the user itself, still there are some constraints that are automatically inferred by the system itself e.g. perpendicular and parallelism. The application of constraint knowledge to graphical displays automatically allows for better control of the design space and facilitates an incremental re-design of a generated presentation, and a description of complex objects simply and naturally. Employing constraint knowledge has given the designer the possibility of modelling the history and topology of the features, as well as modelling the constraints applied to objects.

3.3 CONSTRAINTS IN MANUFACTURING

In this section constraint-based approaches to manufacturing problems are described. The modelling of problems with constraints comes to the fore when we think about the manufacture of products is investigated. Consider yoghurt as an example, the customer expects a certain smell, texture, colour and taste. The manufacture of the product changes these parameters once the yoghurt is mixed; the product "shear thins" lowering the thickness presenting an immediate conflict. If the manufacturer reduces processing speeds to alleviate this, their costs increase. The introduction of fruits, colourings and preservatives to the product, and the fact, that it is produced in a number of forms; drink, solid and semi-solid. Only adds more constraint into the model. With this in mind the constraint-based approaches are employed to model and analysis production processes and products. The section is divided in four sub-sections; product and process analysis, product and process layout, planning and scheduling, this section end with a brief discussion.

3.3.1. Product and process analysis

Product and process analysis is the stage of the product lifecycle when a fully developed product and/ or its related process are optimized to aid manufacturing. Abdalla (1998) develops a knowledge based constraint network system to maintain design consistency and support the selection of appropriate manufacturing processes according to pre-defined constraints. The system is aimed at the machining element of manufacture. A number of constraints related to existing manufacturing facilities and expertise are formulated and modelled using rules of knowledge based toolkit. When the designer modifies any variable value, then the system also updates all constraints automatically. The system also starts to propagate all the updated constraints as the propagation is performed. Each affected constraint is automatically re-assessed since it status might vary to change, which occurred to a variable value. The system aims to consider design and manufacture concurrently. The author claims the system has the capability to determine whether a part can be manufactured 'in-house' with available manufacturing facilities and provide feedback related to machining concerns that may rise.

In Chatelain and Fortina (2001) an approach is presented for balancing blank casting and forging components based on a direct search technique. The outcome is to find whether a component can be machined to final specifications without suffering from any shortage of material, and addresses how any shortfall of material can be re-oriented to reduce re-work if no feasible solution can be found. The approach was tested and proved on a hydroelectric turbine blade. Daley and Liu (1995) applied direct search optimization to attain the parameterised information for the tuning of Proportional, Integral and Derivative (PID) controllers. The approach was tested on a hydraulic system with problematic dynamics and for combustor emission control problem, which had slow dynamics and a large time delay. In Fernando *et al* (1999) the authors propose a constraint-based environment for supporting assembly and maintainability of virtual component prototypes. The approach is aimed at supporting and assessing two handed assembly and disassembly operations. Within the environment the user is allowed to manipulated objects to investigate their assembly. The system checks for collisions and interactions between objects.

Recent attempts have been made to find the optimal process conditions for products, as many optimization problems are limited by constraints. In the search for the optimal metal removal rate for surface grinding the author of Lee *et al,* (2006) employed particle swarm optimization, their derived the surface finish and surface flaw constraints from statistical data taken form previous testing. In another approach for surface grinding, Krisma and Rao (2006) use an evolutionary approach named Scatter Search (SS). The advantage of this technique lies in the fact that it does not get stuck in local minima like other evolutionary algorithm approach. They also included the constraints of machine tool stiffness and wheel wear rate in their approach. To find the minimum production cost through optimal cutting conditions in milling operations, Screeram *et al,* (2006) used a genetic. To find the minimum production costs for multi-pass turning the authors of Satiskumar *et al,* (2006), investigated three techniques: simulated annealing, genetic algorithm and ant colony optimization. The techniques had to handling the constraints of max/min feed rates, cutting force/power, surface finish and depth of cut. The authors indicated that ant colony optimization gave the best performance.

Another approach for this problem was given by Gelle *et al,* (2002) where the authors developed a hybrid algorithm from simulated algorithm, genetic algorithm and Chromosome Differentiation (GACD-SA) (selecting number of passes and depth of cut). The approach included a strategy for maximizing the hamming distance (chromosome differentiation). In comparison with a classical genetic algorithm, the approach offered an enhanced balance between the exploitation and exploration, and simulated annealing checks for entrapment of solution local optima. In an attempt to produce an approach for all machining processes, Zhang *et al,* (2006) use a population based algorithm MIEA (mixed integer evolutionary algorithm). The algorithm incorporates methods to handle boundary, equality and inequality constraints. The algorithm includes a problem independent penalty scheme.

With machine systems designed, another area that has to be assessed is the effectiveness of the user working on the system. Vera *et al,* (2004, 2005) have employed constraint-based approaches to predict and investigate the prediction of skilled performance of individuals using machinery. Their initial approach named Cognitive Constraint Modelling (CCM), their system outputs a prediction of time course interaction; this is taken from the input of the description of the constraints on a task environment, on user strategies, and on human cogitative architecture. Their reasoning for choosing a constraint-based approach was the potential to provide a formal framework for specification of theories of interaction cognition. The benefits of the approach were two fold:

(i) As the constraints are additives, a clear division can be seen between task specific, strategy specific and physiological constraints. This further ensures reusability of the appropriate constraints as new models are built.

(ii) As constraints are declarative, divisions are possible between what is to be computed and how it is to be computed. This gives the authors the important relationship between the constraints on cognition and that of any algorithm used.

3.3.2. Product and process layout

This is the area of the product lifecycle when the engineers search for optimal configurations of plant and equipment. This also takes into account the interactions with operator. Kopcke *et al,* (2006) used a constraint satisfaction problem approach to solve the over-constraint problem of plant layout. The constraints are represented by fuzzy relations. The constraints are satisfied to a degree of acceptability to form a potential solution (Dubois *et al,* 1996). To solve the fuzzy constraints a partial forward checking (PFC) algorithm is employed. Variables are instantiated sequentially and the effort of a tentative value selected is propagated to each of the unassigned variables. The advantage is to increase the likelihood that a good or ideally optimal solution can be found early. This is accomplished by ordering the variables in each domain according to the satisfaction degree of a singular constraint and ordered the variable on a basis of first fail heuristic (Bacchus and Van-Run, 1995). The heuristic employed selects first the variable with the minimum number of values in its domain. They used eighty eight constraint rules to define plant layout relations, and verified the approach on an existing chemical plant. The constraint satisfaction approach designs with similar performance with respect to the role but did not consider other criteria. Another approach along the same lines is Medjboub *et al,* (2002) who developed an interactive constraint-based approach to the optimal design of piping layout. They employed an enumeration algorithm to find the objective criteria of minimum pipe length and bends within a 3D geometric space.

In Shen *et al* (2005), the authors proposed a generic approach based on a direct search algorithm for the three dimensional layout of component. Case studies to prove the approach were performed on packaging of gears, automotive engine layout and heat pump layout as discussed in the motion planning section, new directives and regulations affecting the use of industrial processing machines require companies to take greater care and responsibility for the machine operators. Such new legislation, together with an increase in legal responsibility for operator safety, has made it necessary for companies to demonstrate that they have taken all due care in insuring the safety of ensuring their machines and there layout within the manufacturing environment. (Molenbroek and Medland, 2000). Simulation of human modelling is being used to investigation these interactions between human and machines layout. In Medland and Mitchell (2005) utilised the constraint modelling software “SWORDS” (Mullineux, 2001) to investigate a range of research orientation issues within human modelling. Rules were expressed to form constraints on a created manikin model during a desired action with articulation governed by connectivity constraints at each joint. Thus, critical actions that must occur for a movement type to be successful could be described as a series of task objectives (constraints), and manikin movement could be created between successive critical actions. The advantage of such a model is that large numbers of subjects do not initially have to be studied and realistic postures can be created despite a changing environment or starting position. This work was later expanded by Mitchell *et al,* (2007) in stability assessment of a given posture to determine and analyse the centre of mass in relation to the base of support provided by the feet or other body part in contact with the ground. This enhancement gives the user the potential to simultaneously assess and modify a machine design to suit an operator.

3.3.4. Constraint aided planning

Over the past two decades constraint based approaches have been implemented to aid the planning process. For the purposed of this thesis planning is considered under two headings:

(i) Computer aided process planning (CAPP), where the constraints are employed to find the best solution to the processing of parts or the utilization of manufacturing equipment that are used in the manufacturing domain, and

(ii) The motion planning of devices such as robots and manipulators which are used in the production transfer and assembly functions of the manufacturing domain. This section will also include some work on virtual motion planning.

3.3.4.1 Computer aided process planning (CAPP)

The majority the research that has been performed in the area of CAPP, has been employed in the area of manufacturing components, this is mainly due to the fact that such processes are is easily decomposed into the manufacturing steps and manufacturing features are easy to identified. This work has been performed for the manufacture of turned components Reddy *et al,* (1999); the bending of sheet metal parts Vancza and Markus (1991) and milling of prismatic parts, (Li *et al,* 2002, 2004, Ding *et al,* 2005); optimal drilling sequence planning (Omubolu and Clerc, 2004). In our investigation of previous research I have identified eight generic constraints that needed to be resolved, for computer aided process planning. *Datum interactions*: occurs when machining removes a feature that is a datum surface required by another feature:

- *Feature priorities/ precedence*: certain features need to be machined before others.
- *Fixed order of operations:* some features require 'rough' machining or material clearance before the require machine process.
- *Fixture constraints*: pre machining of clamping surfaces may be required, these surfaces may need to be retained until the end of the process for further setups.
- *Material removal interactions*: where an individual process may have cost or quality effects on the finished product.
- *Thin wall interactions*: features of the product may be distorted by the machining process.
- *Tool interactions*: the machining of one feature may remove the surface of existing or pending surfaces; in bending operations the process may cause collisions between the component being formed and tooling.
- *Manufacturing alternative*: is there another way to process the operation.

In order to find the best solution for process planning, solution criteria have to be established. The one common factor from all the research surveyed is cost reduction. This has been found by the reduction of number of setups, tool changes and machine changes. The satisfaction of constraints using these criteria has been performed using meta-heuristic strategies; genetic algorithms were employed in Ding *et al,* (2005), simulated annealing and Tabu search (Reddy *et al,* 1999). Other researchers have opted to employ constraint programming language techniques Vancza and Markus (1991); this offers the researchers the flexibility to employ techniques such as Pareto optimization. Onwubolu and Clerc (2004) defined the drilling sequence as a 'travelling sales man problem' then employed PSO to find the best solution.

The next step after planning the manufacture of parts is the assembly process. Rajan and Nof (1996) developed an approach to find the minimal precedence constraint for assembly process. Their approach was developed from that of DeFazio and Whitney (1987), who had employed mating precedence constraints to describe constraints, earlier for component liaison of the assembly process of a ball point pen. A component in an assembly has the constraint of all other component which 'mate' with it, lease are the liaisons. Their objective was to find the smallest set of constraint that can exist for an assembly, to ease the overall planning process. While their approach dealt with the constraint associated with component assembly, they where also concerned with the representation of the constraints for use in motion planning for assembly equipment, here attempting to develop a global exaction plan for the product cell. For flexible automated assembling of product noted in Rajan and Nof (1996), specific tooling is required, namely robots and there inherent manipulators. This is another area where constraint based techniques can aid the planning process.

3.3.4.2 Motion planning

The essential idea behind the motion-planning (MP) problem is, to map a collision free motion for equipment moving among obstacles between start and goal locations, or to conclude that no such motion exists. MP techniques determine the motion of a robot and manipulators in their configuration space (c-space). The motion planning problem can be categorized under two approaches; global and local. Global approaches are guaranteed to find a complete path, although they use have high computational time. Local methods use lower computational time but are not guaranteed to finds a solution. All the publication identified in this review employs global appraoch. Examples of system that employ MP are robot welders in car assembly, pick and place machines and paint robots on assembly line.

Ferbach *et al,* (1994) introduced the theory of progressive constraints. The original problem is replaced by a series of progressively constrained ones. The intention is to make the intermediate solution converge to a solution of the original problem. The constraints for the technique are joint limits, manipulation and obstacles avoidance. They employed variational dynamic programming (VDA) to iteratively produce a sub-manifold from the current path to search for a better solution. Sutano and Sharma (1997) proposed an iterative method strategy to deal with the problems of probalistic road maps and random trees when applied to motion planning by constraint relaxation of feasible constraints. The feasible constraints were; robot kinematics, control system and visual tracking. They employed a constraint-relaxation strategy, of the feasibility constraints to find a satisfactory solution. The information from this solution e.g. collision points is used to solve the proposed problem. The objectives for solution are, minimizing joint movement and relative velocity.

In the search for the optimal 'pose' trajectory for robot manipulators, in Cartesian space. Zha (2002) has to deal with the system constraints for: kinematics, dynamics and control performances; reachability, joint range availability, manipulability and joint torques. For this purpose he employs GA enhanced optimization. The method was used to select the parameters of the space curves, so the PRS and its area and area change ratios are optimized for achieving good kinematics and dynamics performances. Garber and Lin (2002) produced a framework for MP in virtual prototyping applications. They treated MP as a constrained dynamic simulation. The authors use hard and soft constraints to enforce relationships and guide robots behaviour and to find the best path solution. The hard constraints are solved by implementing iterative relaxation, and a penalty based method is used to represent the soft constraints. Case studies from automated assembly and paint lines were used to prove the approach.

3.3.5 Scheduling

Production scheduling is defined as "the allocations of available production resources over time to best satisfy some set of criteria" (Graves, 1996). Elaborating on this definition, the goal of manufacturing scheduling is to determine the optimal assignment of process equipment and resources to production. The rising complexity as identified by in scheduling process and increased competition in industry has created a great deal of interest in scheduling research in the past decade. The interest in this area of previous research in respect to the research presented in this thesis, come form the diverse nature of problem area and how constraint-based approaches have been employed for the redesign of schedules (re-scheduling).

3.3.5.1 Job shop scheduling

The job shop scheduling problem (JSSP) consists of a given a set of jobs with a set of machines. These machines can process at most one job at a time. Associated with the job is a group of operations, each of which needs to be processed during an uninterrupted time period of a given length on a given machine. The problem is to find a schedule of minimum time for the allocation of operations to given time scale on each machine. In Bares *et al,* (2000), the approach is examined, building the schedule incrementally by the addition of precedence constraints. The results showed that solutions are obtained in less time than it took to generate comparable solutions with other techniques. Sahed and Fox (1996) modified their earlier work (Sahed and Fox,1995) on the same topic and presented a new probabilistic framework to captures the knowledge of the key aspects from job shop scheduling search space, employing precedence and capacity constraints. Beck (1992) described a general mechanism for identifying constraints violations and monitoring the threat to the satisfaction of the scheduling constraints (TOSCA). The idea is that the earlier the failed states are identified, the less unnecessary work needs to be done.

3.3.5.2. Batch processing scheduling

Another specific scheduling problem is batch scheduling, Fischer (1990) defines a process as batch when "if due to physical structuring of the process equipment or due to other factors, the process consists of a sequence of one or more phases that must be performed in a defined order". The completion of this sequence of steps creates a finite quantity of finished product. If more of the product is to be created, the sequence must be repeated. An approach was proposed by Huang and Chung (2000) for the scheduling of pipe less batch plants. Constraints on resource allocation, activity precedence, time bounds and safety issues are considered. And the objective was the correct resource allocation. A case study was presented to demonstrate the applicability of the system, showing correct allocation of resources. Das *et al* (2000), time-based and Activity-based approaches to production scheduling in the chemicals processing sectors were investigated.

3.3.5.3. Re-scheduling

The dynamic nature of the production environment means that schedule revision is often required, this is termed rescheduling. Kelleher and Cavichiollo (2001) note how preparation effects from the old schedule require extra constraint to be considered, such constraint are applied dependant on 'how far down' the production cycle. To overcome this, the authors divided the process into zone and each of these has different scheduling rules. When the schedule has localized specific problems, the dependency analysis is employed to aid reconstruction of the schedule. The approach was studied on batch process machines, employed in tyre production. Hoitomt *et al* (1990) developed a methodology for scheduling jobs on parallel machines. They use precedence constraints, and the emphasis of their methodology is based on synchronous manufacturing philosophy where ‘bottle-necks’ are deemed to control product flow. Job interaction competition is employed to answer ‘what-if’ scenarios. These allow for reconfiguration of the schedule to accommodate new jobs.

3.3.5.4 Human machining scheduling

An interesting extension to dynamic nature of scheduling is, the scheduling jobs executed by human resources in a contaminated area (Janiak and Kovalyov, 2006). The specificity of this problem is that the dynamics of the harmful factor should be taken into account as well as the norms of organism recovery in rest periods. The harmful nature of the environment means that each work period for a job is accompanied by a rest period whose length depends on the start time of the work period and its length, employing when precedence and non precedence constraints. Creemer *et al,* (1995) presented PLANETS, a prototype constraint-based system to find the optimal maintenance schedules for an electrical power distribution network. The system takes into account nine types of constraints: resources, precedence, consumer, continuity, switch-behaviour, radiality, overload, energy-demand and due-date. From the user’s point of view, the benefits come from the minimization of the total amount of undistributed energy coming from forced maintenance. The system used the constraint logic programming language CHIP. Gomes and Vale (2003) presented similar work to that of Creemer, but they investigated the capability of specific heuristics for the approach. Deris *et al,* (1999) presented a constraint-based approach to optimize the maintenance scheduling of ships. They employed genetic algorithms to deal with ship availability, maintenance resource and precedence constraints. The approach was developed for the Royal Malaysian navy.

3.3.6 Manufacturing discussion

As with the design section the following table 3.3 gives an overview of the previous research presented in the manufacturing sections 3.2. It presents the problems that the researchers have tried to address and presents the constraint handling technique which the researchers have employed.

Table 3.3 Manufacturing constraint-based approaches

Author	Aim /contribution	Manufacturing task	Domain	Constraint handling	Constraints	Objective criteria / goal	Case study
Abdalla (1998)	concurrent design	Product optimization	Product	Satisfaction	Design and manufacturing requirements	Reduced costs	Milled parts
Bares *et al* (2000),	Model for constraint-based camera positioning	Process analysis and optimization	Virtual systems	Optimization	Object project, views, occlusions, field of view	Arbitrary views	Camera simulation
Beck (1993)	Optimal scheduling	Scheduling	Product	Checking	Capacity	Reduction in production bottlenecks	Hypothetical job shop schedules
Chatelain and Fortin (2001)	Finding product machinablity	Computer aided process planning	Process	Optimization	Component measurements	Machining ability	Propellers
Creemer *et al* (1995)	Scheduling of power- distribution Maintenance	Scheduling	Electrical system	Optimization	Resources, precedence, system operation	Minimization of undistributed energy	Power distribution networks
Daley and Liu (1999)	Finding parameters for control	Layout/ configuration	Electronic	Optimization	System dynamics	Optimal control parameters	Hydraulic system
Das *et al* (2000),	Process scheduling for batch production	Scheduling	Process	Optimization	Time	Minimal make span	Chemical process
Ding *et al* (2005)	Use of features for process planning	Computer aided process planning	Process	Optimization	Precedence, feature interaction	Minimal make span and cost	Prismatic parts
Ferbach and Barraquand (1994)	Motion planning of manipulators	Computer aided process planning	Process	Optimization	Joint limits, manipulation and obstacle avoidance	collision free path	robot manipulator
Fernando *et al* (1999)	Virtual environment for assemble and maintenance tasks	Process analysis and optimization	Product	Checking	Component interactions	Analysis of assembly and disassembly	Aerospace systems
Garber and Lin 2002	Virtual motion planning of robots	Computer aided process planning	Virtual systems	Optimization	object non-penetration, joint connectivity and limits	attraction, obstacle repulsion, path following	Robot
Gelle et al (2002)	Constraint satisfaction methods for engineering	Product optimization	Structures	Satisfaction	Design solution space	Optimal construction of structures	Single storey building
Hoitomt *et al* (1990)	parallel machine scheduling	Scheduling	Process	Optimization	Precedence	Minimal make span	Machine scheduling
Huang and Chung (2000)	Scheduling of pipe-less production plants	Computer aided process planning	Process	Optimization	Precedence, time and safety factors	Minimal make span	Pipe-less schedules
Janiak and Kovalyov (2006).	Job scheduling for operators working in contaminated areas	Scheduling	Process	Optimization	Precedence and rest periods	minimum duration	Contamination area clearing plan
Kelleher and Cavichiollo (2001)	CSP for rescheduling	Scheduling	Process	Satisfaction	Precedence	Minimal make span	General scheduling examples
Kopcke *et al* (2006)	Optimal plant layout	Layout/ configuration	Chemical	Optimization	Part positions and orientations, relative and absolute positions	Optimal layout	Chemical plant
Krishma and Rao 2006	Finding best machining parameters	Process analysis and optimization	Process	Optimization	Thermal damage, machine tool stiffness, wheel wear, surface finish	optimal grinding conditions	surface grinding
Lee *et al* (2006)	Partial swarm for grinding processing	Process analysis and optimization	Process	Optimization	Surface damage	Optimal metal removal	Grinding
Li *et al* (2004)	Tabu search for computer aided process planning	Computer aided process planning	Process	Optimization	Precedence	Minimum machine change and make span	Prismatic parts

Medjdoub *et al* (2002)	Piping layout	Layout/ configuration	Hydraulic/ pneumatic	Satisfaction	Topology, dimensional, inclusion of room, non-overlapping, adjacency	minimum pipe length, bends, surface area	Piping layout
Mitchell (2003)	Assessment of centre of gravity for human motion	Human modelling	Virtual systems	Satisfaction	Motion, position, connectivity between elements	Centre of mass/ balance	Manikin stair climbing
Matthews *et al* (2006c).	Assessment of machine capability	Process analysis and optimization	Process	Satisfaction and checking	Design laws, kinematics, product factors	processing of variant product	Food processing equipment
Mitchell *et al* (2007)	Human model ergonomics	Human modelling	Virtual systems	Satisfaction	Motion, position, connectivity between elements	Desired posture and motion	Manikin
Gomes and Vale (2003)	Scheduling of power- distribution Maintenance	Scheduling	Electrical systems	Optimization	Resources, precedence, system operation	Minimization of distribution down time	Power network
Omubolu and Clerc (2004),	Drilling sequence planning	Computer aided process planning	Process	Optimization	Precedence	Minimal make span	Part drilling
Reddy *et al* (1999),	Planning using genetic algorithms	Computer aided process planning	Process	Optimization	Order of operation	Minimum machine change and make span minimization	Milling of parts
Rajan and Nof (1996)	Motion planning with constraints	Computer aided process planning	Process	Optimization	Sensor limits	Cost minimization	Robot
Sahed and Fox (1996)	Production of optimal job shop schedules	Scheduling	Process	Optimization	Precedence	Minimal make span	General job shop schedules
Satishkumar et al (1996)	Optimization of grinding process using hybrid strategy	Process analysis and optimization	Process	Optimization	cutting force/ power, surface finish, max/min feed rates	minimal product cost	Surface Grinding
Sharma and Sutanto (1996)	Virtual motion planning of robots	Computer aided process planning	Virtual systems	Optimization	visual	visual tracking, robot kinematics	Robot
Shen et al (2005)	Layout of mechatronic components	Layout/ configuration	Electronic	Optimization	device housing, component placing, interface, wiring restrictions	Minimal layout	Handheld mechatronic device
Sreeram et al (2005)	Dry milling optimization	Process analysis and optimization	Process	Optimization	Max/min bounds of cutting parameters	optimal cutting parameters	Coolant free micro-milling
Sutanto and Sharma (1997)	motion planning using constraints	Computer aided process planning	mechanical systems	Optimization	Sensor	Kinematics, control system, visual tracking	Robot system
Vancza and Markus (1991)	Planning using genetic algorithms	Computer aided process planning	Process	Optimization	Precedence	Minimal make span	Machining
Zha (2002)	Collision free motion planning	Computer aided process planning	mechanical systems	Optimization	kinematics, dynamics, control performance, reach ability, joint	Optimal pose trajectory	Serial robots
Zhang *et al* (2006)	Optimization of multi-pass turning	Process analysis and optimization	Process	Optimization	Cutting force/ power, surface finish, max/min feed rates	Minimum make span	Turning

Constraints provide declarative descriptions of important requirements relating to approaches for: planning, scheduling and as an analysis tool. Constraint approaches have proven successful for the production of process plans for manufacture (Ding *et al,* 2005; Li *et al,* 2002, 2004) and assembly of components (Nof, 1996). It has also been successfully employed for collision free motion planning for robots and manipulators that are employed to assemble weld and paint in modern production lines. The follow on from this is the virtual motion planning of devices, including camera position planning in simulation software Gaber and Lin (2002). The constraints give the user knowledge of the acceptable manufacturing sequence. In the case of motion planning they offer knowledge of what is obtainable for the robot or manipulator. As with process planning constraint-based approaches have proven successful for a variety of scheduling problems: batch, job shop and most importantly for this research constraint-based approaches have shown potential for re-scheduling. The constraints in scheduling give the knowledge of the manufacture sequence; as with process planning, this predominately precedence. But the inclusion of constraints relating resource allocation, time bounds and manufacturing safety, allow the engineer a greater understanding of the manufacturing problem.

Within the manufacturing support section, it has been shown that for a diverse area of problems, that engineers have recently employed constraint-based approaches to assist and solve manufacturing issues, for example this can allow the engineer to investigate capability and capacity envelopes of processing equipment (Matthews *et al,* 2006c). Knowledge of the constraints can assist the production engineer to find good manufacturing set-ups and processing conditioning (Krishma and Rao, 2006), Daley and Liu (1999). They aid engineer in the over-constrained area, of plant layout for processing equipment Kopcke *et al,* (2006) or space saving way of packaging product Shen *et al,* (2005). For human machine interaction with machines in the industrial environment, constraints-based approaches are being employed to simulate the human operation of processing equipment (Mitchell *et al,* 2007) to aid designers and manufacturers in the conformance of new legalisation.

3.4 CONSTRAINT-BASED APPROACHES DISCUSSION

Sections 3.1 and 3.2 have identified and reviewed approaches that have employed constraints as a means of representing the relationships, requirements, internal and external limitations of given systems. The singular factor that is constant across the domains of manufacture and design is the inherent activity constraints. The knowledge of these is essential in the compromise to find the best practical solution to a design problem, and negotiating the best strategy to manufacture the resultant product. The constraints offer knowledge of the limits, relations and goals of a presented problem.

A limitation of the some of the proposed constraint-based approaches such as Thornton (1996), Zhang *et al,* (2002) and Honmann and Thornton (1998) lies in the fact that they only work if an adequate library of components, interfaces, and features is available. With the work presented in this thesis, the range and diversity of variant products that manufacturers have to deal with, the existence of such solutions in a library is unlikely. The approach presented in this thesis has to be flexibly and offer an appropriate solution for each problem presented.

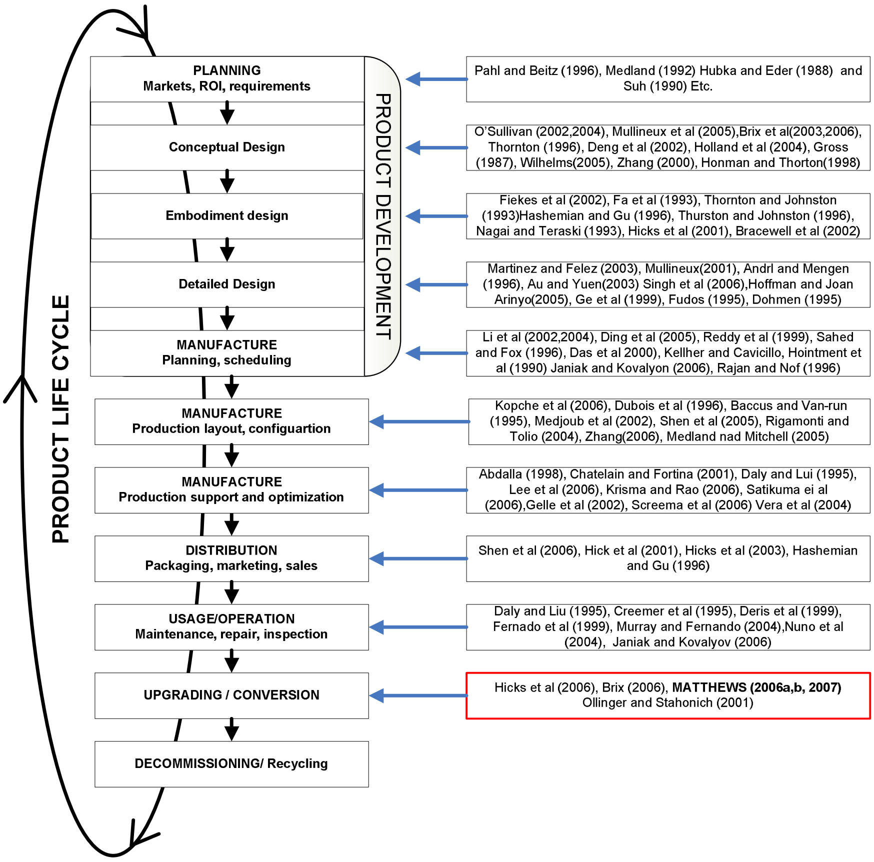


Figure 3.1Product lifecycle

Figure 3.1 is a typical product lifecycle model (modified from Pugh, 1980 and Zied, 1990). As mentioned in the introduction to this chapter. A common factor to all major design theories, as mentioned in chapter 2 at the planning and clarification stage, is the identification of task-specific constraints for the design. Is has not been specifically identified in this chapter, but is shown in figure 3.1.

It shows how recent constraint-based approaches populate most stages of the life cycle. The research of this thesis is concerned with the "upgrading and conversion" of systems. Disregarding the publications that have been generated from this research (Matthews *et al* 2006b,c and Matthews *et al* 2007a). There are three set of constraint-based research that has been reviewed in this chapter which fit into this problem state.

- Hicks *et al,* (2001): This paper presents an approach for re-design, the approach does not specify how performance needs to be quantified or how the limits for a system are to be established. The research in this thesis presents an approach directed towards this. "Limits modelling" (Matthews, 2006b, 2007a).

- Brix *et al,* (2003): Although their research was aimed at conceptual design, the authors presented that the tool could support the reuse of design solution principles from different information sources and their adoption to current requirements. The limitation of this approach comes from the fact that it only supplies potential concepts and does not embody the design or assess the performance. The research presented in this thesis does offer performance assessment and embodied values for the design.

- Ollinger and Stahonich (2001): The emphasis of this work has been the production of design plans for potential solutions. As the tool is developed for the early stages for the redesign process, it results in solutions with no numerical design quantities. The tool also assumes that the design solution will always function. There is no capability to change functionality. The approach presented in this thesis offers this potential.

Excluding the individual limitations identified above for each paper, a common factor with each is that none of them take into account the product and its related constraints. In the research reviewed to date, no constraint-based approach has been identified to investigate the handling of product variation on existing equipment.

3.5 CHAPTER CONCLUSION

The aim of this chapter has been two fold:

- Firstly, to satisfy objective 2 from the introduction; “to demonstrate the effectiveness of product and process constraints in the design and manufacturing domains”. This chapter has presented how constraints and their respective approaches aid both design and manufacturing.
- Secondly to identify the constraints which an approach such as that presented in this thesis must consider for a problem which span the design and manufacturing domains. These constraints have been presented in tables 3.2 and 3.3 along with the domain specific problems they had been employed for. These are summarized in table 3.4, for design activities the constraints are the goals and relationships of a given problem, for manufacturing the constraints form the limits or bounds of the activity.

Table 3.4 Summary of design and manufacturing constraints

Domain	DESIGN	MANUFACTURING
Constraints	Geometric Function requirements Relationships between functions Connectivity between elements System topology	Motion limits Position Kinematics Component damage Component interaction Precedence

The chapter has also shown how previous constraint-based research aids the whole product lifecycle, and how this current research fills some gaps in the research. The next chapter presents the theory for implementing a constraint-based to address the problem presented in this chapter.

Chapter 4

The theory

"A theory can be proved by experiment; but no path leads from experiment to the birth of a theory"

Manfred Eigen

It has been identified in the previous chapters that there is a specific need in industry to understand the potential capabilities of the mechanism from production machinery, especially its capability to process variant products. This chapter explains the reasoning behind the selection of a constraint-based modelling approach to investigate this problem. It carries with explanation on how the identification of the limiting factors (constraints) of both the equipment being investigated and the product to be processed are of prime importance to any approach being employed. The chapter also explains how such constraints need to be handled in any modelling approach being applied. This chapter presents the investigations of key objective 3 from chapter 1

4.1 WHY A CONSTRAINT-BASED APPROACH?

What has become evident from the research reviewed in chapter 2 is that there is currently a variety of underlying methods for application assessment, analysis and problem solving that could potentially be applied to the issues discussed in this thesis. The main reason for this stems from the fact that particular tools or techniques are frequently driven by the perspective of the particular problem and how it is to be solved rather than a generalized approach for reasoning about the problem. It is arguable that such variety makes the use, integration, exchange and unification of supportive tools, methods and processes (process elements) particularly difficult. This contributes to many of the research challenges now facing academia and industry (Culley, 1999). In order to create a generalized approach for both modelling and reasoning a constraint-based approach was investigated. As shown in chapter 3, this has recently been applied to a range of different tasks associated with design and manufacture, and forms the background to the approach adopted for the work presented in this thesis.

With the problem stated in chapter 1 in mind, and similar ones in many other engineering sectors, there are a lack of supportive approaches that cover the whole design and manufacturing processes. Many individual tools used in combination can span the overall process, but there are few tools or approaches that provide support over the full range of activities in their own right. So, with the various support strategies available to modern engineers, such as those shown in chapter 2. Why opt to use a constraint-based approach instead of others, in this research?

Firstly, with equipment redesign, the critical factor is the identification and formalization of the functional requirements for the redesign, in respect to the inherent capabilities of the existing design. With the requirements specified, the constraints imposed by the existing equipment and that of the product variation can be formalized for the design problem.

Secondly, when an engineer encounters a new or existing design for the first time, knowledge of the design area is often ill-understood and the appropriate design rules are unclear. What are more apparent are the constraints which place limits upon the allowable forms of feasible design. Such constraints can be the connectivity of machine elements, locations of drives, size of machine base, or they can relate to physical motion limits of the product, for example, a process may originally be to transfer a frozen cake, now it is required to process it in a non-frozen form.

The second point is critical as the current research has highlighted that, at present, such redesign tasks cannot be carried out efficiently in many companies; the inhibiting factors to this include the following.

- The process requires expertise and significant time for novice design engineers to understand a machine. Current representations for machines, i.e. various product models, mainly provide geometrical and topological information, such as assembly relationships, shapes and dimensions. These lack the necessary information for redesign tasks, such as improving performance capabilities.

- It is difficult for novice design engineers to assimilate and digest these redesign processes. Previous redesign processes, including design activities, decisions made and corresponding rationale, are still recorded in text documents (e.g. design reports, meeting minutes) and even retained in employees' memories.

- Over time, it becomes impossible to retrace the engineering reasoning and decision making processes which have taken place during any design/redesign process. How is the companies to understand the limits to the machines capabilities

While investigating the problem, four identified scenarios for machine design and manufacture and operation have been found:

Scenario 1: Smaller UK manufacturing companies often purchase processing equipment, second-hand from dealerships. With such purchases, there are unlikely to be a full documentation set, service manuals and history.

Scenario 2: Manufacturing companies can inherit processing machinery after a business take over. Machines may then be moved to another production site. As with scenario 1, this can lead to deficiencies in the machines documentations.

Scenario 3: Manufacturing companies may run processing equipment for a long period of time, and so specific knowledge of the machine may be lost as the technician or engineer retires or moves companies.

Scenario 4: Some UK food companies purchase ‘off the shelf’ packaging and processing equipment and customize it in-house. Over time information of the functionality and original purpose can be lost.

With these four scenarios the inherent capability for the machinery is no longer known because of information loss.

As identified in chapter 3, constraints are the relations, limits and goals which define the context of designing. There are many constraints on a design and they come from different sources. Constraints are imposed by nature (such as corrosion), convention, (such as machining practice), and the commercial factors (such as environmental costs). Some are imposed externally, while others are imposed by the designer. Some are site-specific i.e. factory policy, others are not. Some are the result of higher-level design decisions; some are universal, a part of every design. Gravity, for example, is world-wide. Other constraints apply only in certain design contexts. Designers can describe a design activity as a collection of constraints and relations on attributes of the object to be designed. That is, to design is to describe and identify constraints and to specify an object that satisfies all these constraints. Design problems have many solutions. Designers do not find the solution to a set of design specifications; designers find one solution or a small number, out of many alternatives. Although designers may prefer some alternatives to others, all are solutions to the initial constraints. At each step in a design it is possible to choose between alternatives by adding constraints. The addition of constraints is also a part of design as the searching for solutions. The design process consists of adopting constraints and then exploring for "good" alternatives in the region the constraints bound.

In the context of this research constraints are presented to express a region in the design space, not in physical space but in an ‘n’ dimensional mathematical one, where n stands for the number of dimensions, degrees of freedom, or independent qualities in the design; the value of ‘n’ may be large and it can change throughout the design process as variables are introduced or eliminated. Each dimension in the n-space represents one independent variable in the design. Each point in the n-space describes a complete set of variable values. A point in the acceptable region describes a complete set of variable values that meet all the present constraints. Each point can be defined as design 'instance' (Matthews *et al,* 2006b), which represents an alternative solution, or variant. Typically the region contains many such instances. The region need not have a simple shape. It may be large in some dimensions and small in others. It may be connected in one place or in many small "islands". Both the number of dimensions of the space itself and the region within it change throughout the design process. As a design activity progresses, more information is available for decision making. There is a high possibility that conflicts of requirements occur, thus tradeoffs of constraints should be made to resolve conflicts. Thus, the feasible region for the individual constraints do not overlap sufficiently to give an acceptable region. This is defined as an over-constrained problem. Within the context of this thesis, the constraint-based modelling approaches are one that allows a designer to explore these boundaries of a design task and to gain a greater knowledge of limits to design and performance.

4.2 MODELLING WITH CONSTRAINTS

The previous chapter made the case for using constraints to aid the design and manufacturing process and the previous section has presented that constraints offer the design engineer useful knowledge of the design problem. This section describes how the constraints are being used, specifically in modelling. Benyon (1990) describes a model as a, "*representation of something constructed and used for a particular purpose"*

For the purpose of this research the models will relate to the characteristics of the machines and the products that are processed on these machines. Benyon concluded his work by saying,

"A good model is accurate enough to reflect the important detail, but simple enough to avoid confusion. We all use such models because they remove some complexity of reality so that the aspect which interest us stand out"

There are several reasons to use modelling to investigate the capabilities of industrial machinery to process variant products,

- It can give the opportunity to experiment and analyse in a relatively low cost and low risk environment.
- In an industrial environment, the cost of getting it wrong is often very high and carries high risk
- Changes to the real system are sometimes expensive, difficult or even impossible to achieve whilst the plant is in production.

As presented in chapter 2, the early work in the area of constraint modelling grew from studies of the design process, where it had been identified that it was better to deal with the design knowledge itself. It is arguable that all constraint approaches deal with the underlying knowledge, and it is this analysis of knowledge (either relations, bound or goals) that provides the fundamental rules that govern the design and manufacture of a product or technical system. It follows that constraint approaches may offer a more general representation of design and manufacturing knowledge.

There are two types of models that have been extensively used in the modelling manufacturing systems: prescriptive and descriptive.

- *Prescriptive models* are generally employed to construct decisions on the system that is being investigated.
- *Descriptive models* are generally employed for performance evaluation of the manufacturing system. These models can be sub-categorized into analytical and simulation models.

Constraints are used to varying degrees in both forms of models. They can be expressed in different formats: domains, equalities or inequalities. A domain represents a set (unordered) in which the design parameters must lie, while equalities and inequalities describe relationships between design parameters taking ordered (usually real) values. Domains are normally discrete and finite. When the domain becomes infinite (and continuous) the constraint usually reduces to an equality/ inequality relation.

When employing an equality constraint in the models, the design parameters are related to one another to represent the functional dependencies for modelling physical phenomena. An example of this is presented by Chan and Paulson (1987): "*Ohm's law V=IR, defines the relationship between Voltage V, current I and resistance R. Viewing the relationship between I and V, the engineer can investigate variations, when either I or V is modified. When V, I and R are all known, but determined independently, the relationship can be used to check whether Ohm's law holds*".

When constraints are used, there is a need to handle/ process the information with which it offers the engineer. Lin and Chen (2002) highlighted three types of constraint-based approaches employed for design and modelling. These are relevant across into the manufacturing domain. There are three levels of constraint-based approaches: constraint monitoring, constraint satisfaction and constraint optimization.

- *Constraint monitoring* uses constraints to check the solutions provided by engineers.
- *Constraint satisfaction* finds feasible solutions to constraints without considering optimal solution.
- *Constraint optimisation* aims to find the best solutions form alternatives in order to achieve the objectives, subject to constraints.

These three handling approaches can be demonstrated using figure 4.1. This shows a contour plot of an objective function of two variables X1 and X2. Three linear constraints are imposed:

$$G0: X2 \geq 0$$
$$G1: 3X1 + 5X2 \leq 30$$
$$G2: X1 - 2X2 + 2 \geq 0$$

These relate to the lines on the figure. The shaded triangle represents the feasible area. The unconstrained minimum of the function lives outside the triangle. The constrained minimum is at a vertex. If the user employs constraint checking then each constraint is tested in turn. For constraint satisfaction, any point in the triangle needs to be sought, which in this case, could be done by finding and traversing the boundary of the triangle. Constraint optimization would be the constrained minimum.

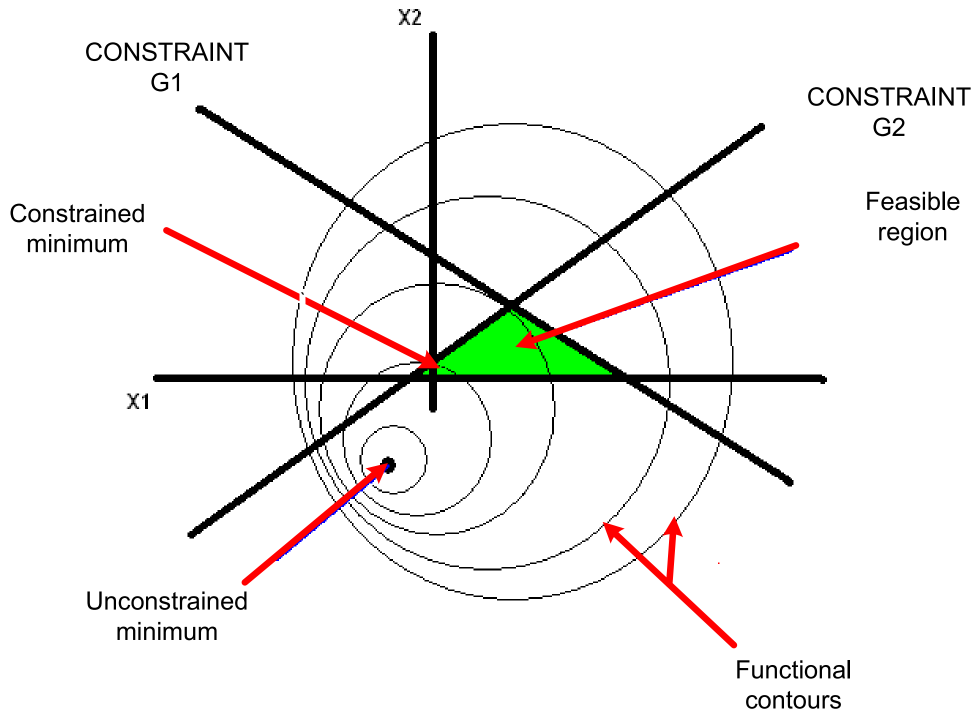


Figure 4.1 Constraint region

With equipment design and development, the constraints can be applied at various levels. These are defined as *hard* and *soft* (Dechter, 2003). In the context of this research such hard constraints are concerned with function and assembly which ensure that the various parts of a system connect together correctly, and, at a higher level, the soft constraints can impose restrictions on performance such as kinematic properties. Additional constraints can relate to equipment cost and operation. Soft constraints may be weighted adjusted and possibly violated, whereas the hard constraints must be true. The application of hard and soft constraints, is relevant to whichever constraint strategy the user employs i.e. constraint satisfaction, optimization or checking.

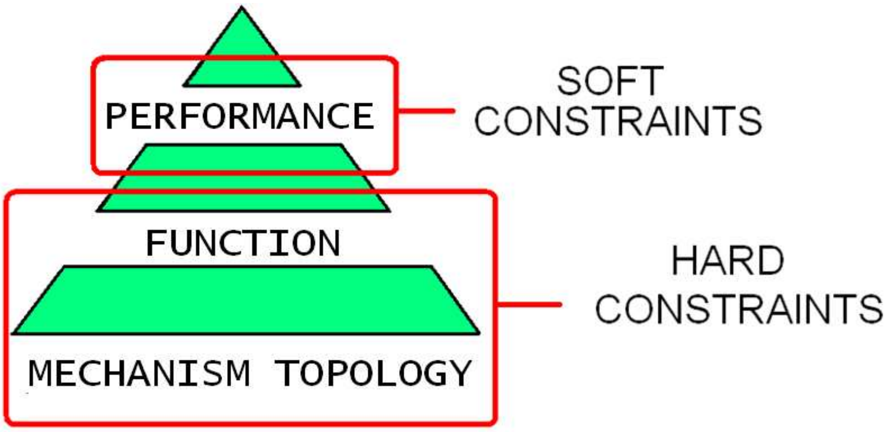


Figure 4.2 Tiered constraints

4.3 EQUIPMENT CAPABILITY

For the assessment of product variables associated with equipment, the critical factor is the identification and formalization of the functional requirements for the design with respect to the inherent capabilities of the existing design. With the requirements specified, the constraints imposed by the existing equipment and these of the variant product can be formalized for the design problem. As shown in section 2.3, modelling and simulation analyse are well established techniques for analysing the potential effects of complex manufacturing changes, without companies committing resources.

With the constraints identified they can be modelled, the option is then open to investigate the other properties which are affected by the constraints. Previous research into task clarification and conceptual design (Hubka and Eder, 1988) has separated the properties affected by the constraints into categories based variously on operational, ergonomic, aesthetic, distribution, delivery, planning, design, production, and economic factors. Besides satisfying the functional and working interrelationships, a solution must also satisfy certain general or task-specific constraints. The review in chapter 3 identified specific constraints that previous researchers had to deal with in the design and manufacturing domains that include (table 3.4):

Constraints in design:

Geometric

Functional requirements

Relationships between functions

Connectivity between elements

System topology

Constraints in manufacturing:

Motion limits

Required motion

Position

Kinematics

Component damage

Component interaction

Precedence

For an overview of constraint-based applications used in the design and manufacturing domains, the above lists are adequate, and are employed in the initial modelling. Unfortunately for the problem this thesis is addressing, they are too vague. With this in mind, deeper investigation has been required, the following section identifies a generic set but not exhaustive set of constraints relating to products to be processed. Building on this the next section identifies a generic set of constraints relating to the machines investigated in this research.

4.4 MODELLING PRODUCT VARIATION

Although this research aims to find a genetic solution to the problem identified in chapter 1, as a starting point this thesis has investigated the products that have to be processed in the food manufacturing and consumer industries. A study was undertaken involving eleven manufacturing companies from these sector industries, relating to twenty five products. Table 4.1 shows examples of variational changes with what the food industry has to cope. In these and other examples shown, the variational changes can be divided into nine distinct categories. Column 2 gives typical example of the variational change, with column 3 presenting the effect on the processing system.

Table 4.1 Product variation effects

Variation Description	Industrial Examples of Problem	System Effects
Increase in product size	Change in product dimensions for over-wrapping	Geometric Kinematic Dynamic Tolerance
Change in packaging density	Two extra frozen puddings per pack	Geometric Kinematic Volumetric
Constituent change	-Customer product variation may force the manufacturer to expand range. The addition of noodles and croutons to dried soup range. -Flavourings used on crisp product i.e. oil or powder	Dynamic Geometric Weight Density Tolerance
Raw product size variation	Potatoes sliced for crisps etc (raw product like potatoes shape cannot be guaranteed, only be graded to a general point)	Kinematic Geometric Dynamic shape Tolerance
Physical properties of product change	Shifting from transferring fruit cake to a soft cream cake or pie. Softer product less resistant to higher kinematics and dynamics	Kinematic Dynamic
Change in packaging materials	Environmental regulations are forcing manufacturers to move towards thinner and biodegradable packaging materials	Kinematic Mechanical properties
increase in product per container	30% extra cereal in a carton.	Geometric Density Weight
Environmental factors	Humidity can change the folding properties of carton skillets. Carton often stored away from product area, this can affect setting of machine.	Kinematic Mechanical properties
Organic product change	The physical properties of potatoes change over the picking season; this has an effect on processing equipment.	Kinematic Shape

4.5 LIMITING FACTORS (CONSTRAINTS)

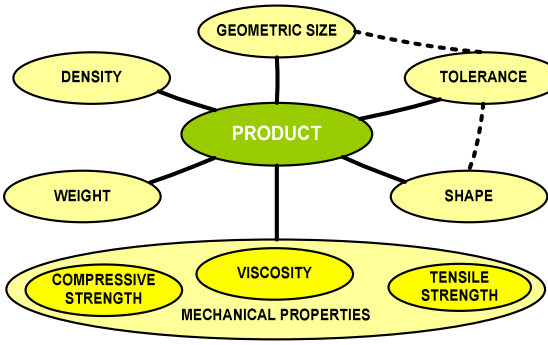


Figure 4.3 Product Constraint factors

The factors shown in Table 4.1 are just a few examples which the food processing industry has to handle throughout the life of a product. When looking at column three, it can be seen that generic product constraint factors arise. The factors are shown in figure 4.3 and include: density, weight, geometric size, tolerance, shape and mechanical properties. Although, the examples investigated only identified three mechanical properties (as shown on diagram), others can be identified such a shear. This research has shown that within the product processing context there is a direct linkage between geometric size, tolerance and shape, this is also reflected in the figure by the dotted line. These can also be seen in the influence diagram in figure 4.3.

Table 4.2 Product constraints

Product Properties	Relationship Constraints	Process Effects
Weight		
	Geometric	
Density		Machine component
	Volumetric	
Viscosity		
	Kinematic	Speed
Geometric size	Dynamic	Capability
Tolerance	Timing	
Shape		
Strength		

The product constraints are summarized in table 4.2. Column one shows the identified product constraints, as shown in figure 4.3. Column 2 contains the relationship constraints of the product. These are the key factors that affect the ability of any system to process variant product (Matthews *et al*, 2007a).

- *Geometric constraints*: these are indispensable for each 'feature', they have a standard range for specifying the value of each parameter for the shape and geometric size. Shape and geometric structure of the product is important when considering retentions for grippers and transfer guides.
- *Volumetric constraints*: these are very similar to geometric constraints, except that the area/ volume the product is important when considering how the product is retained by the manufacturing system and how the product has to be put into containers and packaging.
- *Kinematics constraints*: these are especially important, when considering the transfer of product.
- *Dynamic constraints*: these are important consideration as the product mass increases the forces applied will also increase.
- *Timing constraints*: the ability to move product, changes as factors such as weight and size change with the variant product.

It is the identification of these constraints that need to be applied to any model of the equipment processing a variant product. The associations between the relationship constraints and processing effects (column 3) are further elaborated in chapter 6.

4.6 CHAPTER DISCUSSION

While investigating objective 2 from chapter 1, this chapter has explained the reasoning behind the selection of a constraint-based approach to investigate this problem defined in chapter 1. Namely, when investigating a machine's design for the first time, knowledge of the design area is often ill-understood and the appropriate design rules are unclear. What are more apparent are the constraints which place limits upon the allowable forms of feasible design. Also, with machine redesign, the critical factor is the identification and formalization of the functional requirements for the redesign, in respect of the inherent capabilities of the existing design. With the requirements specified, the constraints imposed by the existing machine and that of the variant product can be formalized for the design problem.

The chapter has presented the variety of constraints which any approach which have to deal with. It identifies the approaches which are to be used, in handling such constraints in a model. Thinking of research by Lin and Chen (2002) relating to design.

There are three levels of constraint handling: monitoring (checking), satisfaction (finding a solution), and optimization (finding best solution). The chapter has identified the constraints relating to the processing of product and the processing equipment taken from industrial examples. From these examples, the chapter has also shown that there are relationship constraints which relate the product constraints to the process.

While this chapter has identified the important factors related to constraints; specifically of the components to be processed and the effects on the processing equipment, the next sections describes the software system that can be employed to handle and satisfy the constraints.

Chapter 5

Constraint modelling software

"All models are wrong, some are useful"
George Box

The previous two chapters, which have identified the rationale for employing a constraint-based approach to the problem stated in this thesis, and identified the relevant constraints which must be handled in both design and manufacturing domains. This chapter provides an overview of the constraint-based modelling package which has been employed in this research. It explains how constraint-based reasoning is used in the construction of models and simulations of machines. The chapter also identifies further specific constraints which are related to the machinery the modelling software has to deal with.

5.1 MODELLING SOFTWARE.

After reviewing the existing approaches to modelling (section 2.2), it was evident that there is currently no singular approach or software solution to deal with the specific industrial question posed in this research. In addition, the previous chapter has presented the rationale for employing and modelling with constraints, and has presented the types of constraints related to modelling machines that the approach must deal with. So, for this purpose, a technique for handling and modelling with constraints is needed. A constraint-based modeller called "SWORDS" (Mullineux, 2001) has been selected to accomplish this task. An overview of the software is presented in this chapter along with a modelling example. The constraint-based system has been selected for this research because of the flexibility it offers the user. Specific advantages are presented below.

- It offers parametric modelling which is paramount to this approach.
- It allows motion and element interaction to be performed.
- Its inbuilt functions give the option of sensitivity analysis (explained in later chapters) and the constraint-based approach using hard and soft constraint allows for optimization.
- Unlike existing software, SWORDS allows the user to interact with and modify the constraints acting on a system.
- Unlike other software packages, the use of constraints eases the modelling of higher kinematic pairs.

The programming environment also permits the user to employ constraint-checking, while actuating and handling models.

5.2 THE CONSTRAINT MODELLER.

The design team at the University of Bath has created the constraint modelling software "SWORDS" (Mullineux, 2001). The software has its own graphical interface for the representation of geometric models (cf. figure 5.1). The software has its own user language which has been created to handle design variables of several types including structured forms to represent, for example, geometric objects. The language supports user defined functions. These are essentially collections of commands which can be invoked when required (the commands used in this thesis are listed in appendix a). Input variables can be passed into a function and the function itself can return a single value or a sequence of values. Functions are used to impose constraints using an unique in-built function which is the “rule” command. Each rule command is associated with a constraint expression between some of the design parameters which is zero (as a real number) when true. A non-zero value is a measure of the falseness of the constraint rule.

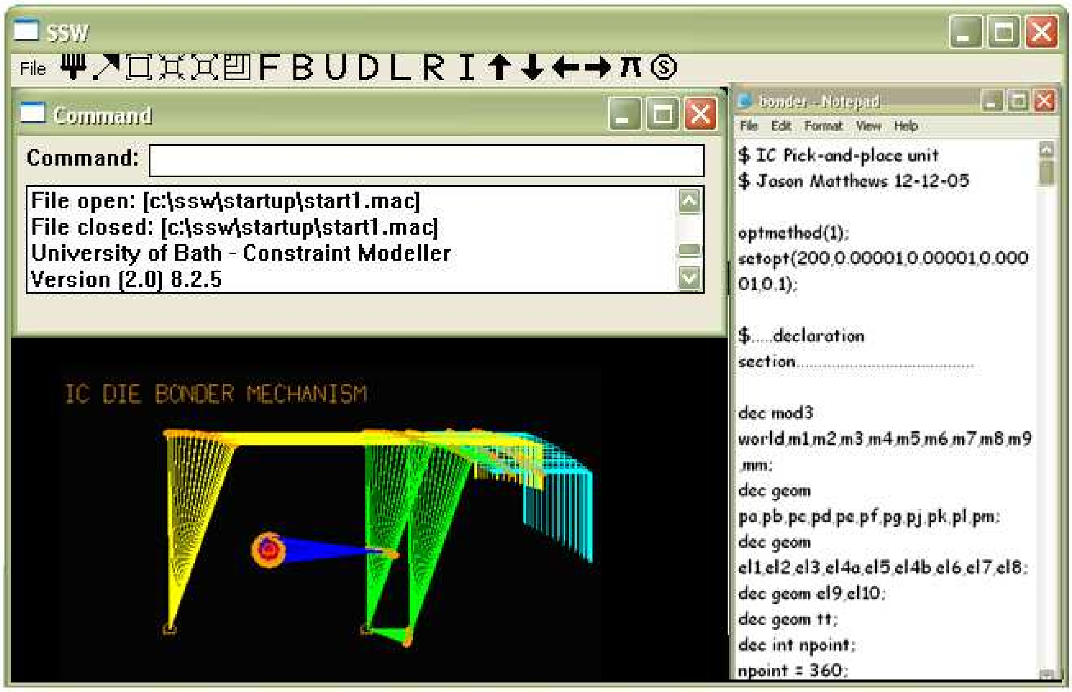


Figure 5.1 GUI screen shot

The software environment supports simple wire-frame graphics, such as line segments and circular arcs. Geometry is supported in the constraint modelling software by creating groups of graphical entities such as points, lines and arc. Each has attributes which can be assigned manually or can be assigned later through the process of evaluating the constraints. Entities can be grouped together to define models or sub-models in order to aid the process of manipulating these entities. Spatial relations between these models are described by allocating a defined space for each of them. The reference space is referred to as the world space which can be used to represents the space of the complete model of the design. Each sub-model has a local space and a transformation matrix is automatically generated for the purpose of manipulation the geometry collectively. The transform maps the space to either world space or another model space this creates a hierarchy of spaces. A two-dimensional model has the following transformation matrix (Leigh *et al,* 1989).

$$\begin{bmatrix} \sigma\cos(\alpha) & -\sigma\tau\sin(\alpha) & X_2-\sigma X_1\cos(\alpha)+\sigma\tau Y_1\sin(\alpha) \\ \sigma\sin(\alpha) & -\sigma\tau\cos(\alpha) & Y_2-\sigma X_1\sin(\alpha)+\sigma\tau Y_1\cos(\alpha) \\ 0 & 0 & 1 \end{bmatrix}$$

The above transformation matrix maps the models space from point (X_1, Y_1) to point (X_2, Y_2). The angle α is the rotation, α is the scale factor and τ is an extra scale factor in the Y direction. The two scales factors are retained as unity for the rigid-body space. This leaves three degrees of freedom for a two-dimensional model space. The same principle can be applied for the three-dimensional case to define the spatial association between the complete model represented in the world space and sub-model local spaces. These matrices are invisible to the user of the system as they are generated and manipulated internality.

Hierarchical representation of the model spaces involved in representing a design in the constraint modeller is achieved by embedding their local spaces into the world or another space. The use of hierarchy allows the relation between neighbouring spaces to be preserved (Leigh *et al,* 1989). Figure 5.2 shows the use of model space hierarchy to decompose a system structure.

Representing assemblies in constraint modelling is performed using the hierarchical and spatial relations at the level of assembly and sub-assembly models. The models of various components can be assembled in a higher level model space which represents an assembly. Extra constraints are needed to describe the conditions of how the various components are to be assembled. The modeller has the capability to use solid objects. These can be embedded within model spaces, so that they can move with other geometry including wire frame entities. Solids have been incorporated into the environment by means of the ACIS library of procedures (Corney, 1997).

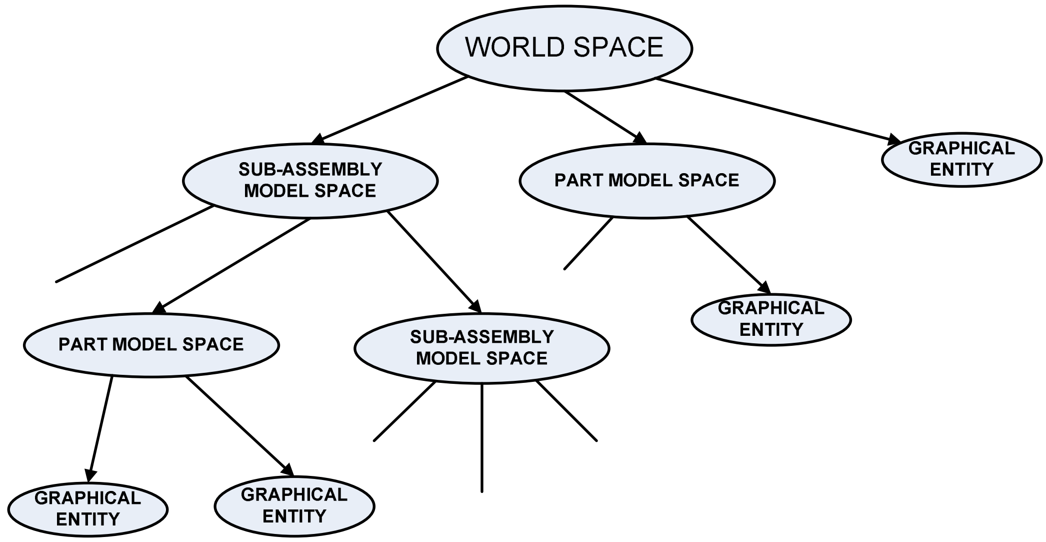


Figure 5.2 Hierarchical structure of a constraint model (Al-Wahab, 1987)

The underlying language of the constraint modeller provides the necessary tools for the constraint modelling system to handle loops, input, output, logical conditions and other facilities normally found in contemporary structured programming languages. This has allowed the system to be interfaced to a number of commercial CAD systems (Singh *et al*, 2006, 2007)

5.3 HANDLING OF CONSTRAINTS

In order to investigate the effects of the constraints, they need to be assessed and handled. There are several techniques for achieving this, such as those presented in Anderl and Mendgen (1996) and Ge *et al,* (1999) including, for example, symbolic manipulation and reordering strategies. The method used by the constraint modeller is based on optimization techniques.

Here the constraint modeller uses penalty functions (Mullineux, 2001); the squares of constraint relations are effectively added into the objective function to reduce the problem to one of unconstrained optimization. If there are n variables $x_1, x_2, \ldots, x_n$ involved in m constraints. These are denoted as follows.

$$F_j(x_1, x_2, \ldots, x_n) = 0 \quad \text{for} \quad 1 < j < m$$

Inequality constraints can be handled within equality constraints using a “ramp” function. For example take the constraint:

$$a + b < c$$

can be represented by:

$$\text{ramp}(a + b - c) = 0$$

where,

$$\text{ramp}(u) = u \quad \text{if} \quad u \geq 0$$
$$0 \quad \text{if} \quad u < 0$$

An objective function is then formed by taking the sum of the squares of these constraints.

$$F(x_1, x_2, \ldots x_n) = f_1^2 + f_2^2 + \ldots + f_m^2.$$

During resolution, the expression for each constraint rule (within a function) is evaluated and the sum of their squares is found. If this is already zero, then each constraint expression represents a true state. If the sum is non-zero then resolution commences. This involves varying a subset of the design parameters specified by the user. The sum is regarded as a function of these variables and a numerical technique is applied to search for values of the parameters which minimize the sum of the squares (Mullineux, 2001). If a minimum of zero can be found then the constraints are fully satisfied. If not, then the minimum represents some form of best compromise for a set of constraints which are in conflict. It is possible at this stage to identify those constraints that are not satisfied and, where appropriate, investigate whether relaxing less important constraints can enable an overall solution to be determined

5.4 EXAMPLE OF MECHANISM CONSTRUCTION

As an example, consider the representation of a four bar linkage shown pictorially in figure 5.3. The constituent parts are shown in fig 5.4. The two fixed pivot points are specified, and the line segments representing the three links are defined, each in a local model space. In the example, the model space of the coupler link ‘L2’ is embedded in the space of the crank, and the spaces for the crank L1 is embedded in world space.

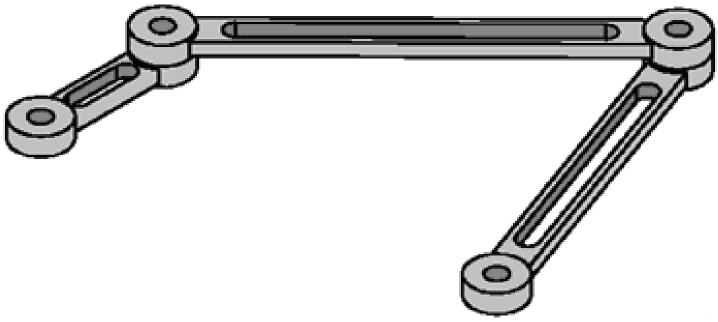


Fig.5.3. Assembly of four-bar mechanism

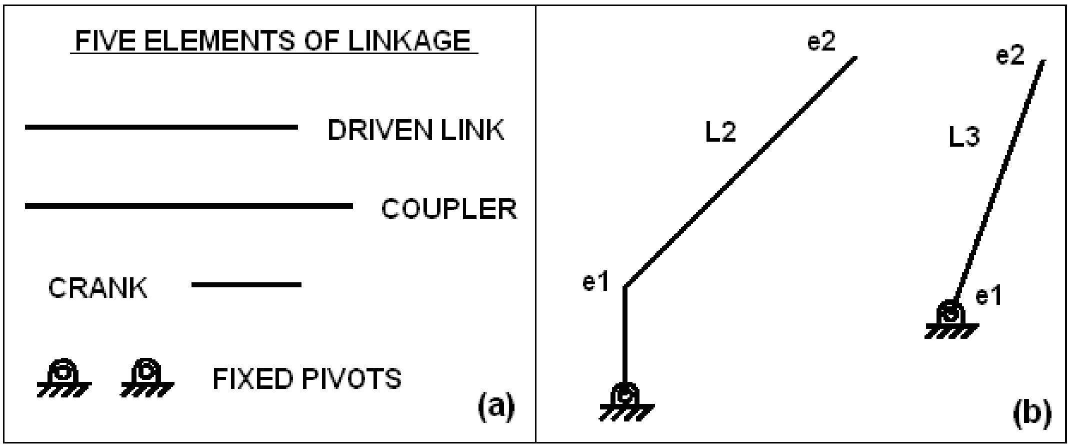


Fig.5.4 Elements of four-bar mechanism

A partial assembly of the mechanism is achieved by applying the transformations to the links in each space. This is shown in part (b) of the figure. If the space of either the crank or the link ‘L2’ is rotated, the hierarchy of their spaces ensures their ends remain attached.

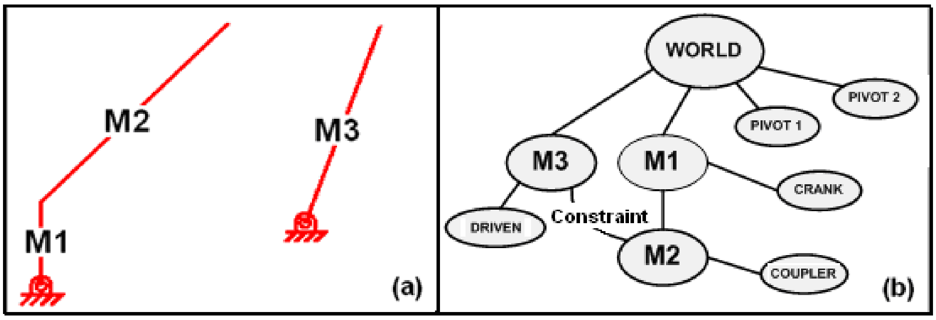


Fig.5.5. Model spaces of four-bar mechanism

To complete the assembly, the ends of the coupler link 'L2' and driven link 'L3' have to be brought together. This cannot be done by model space manipulation alone, as this would break the structure of the model space hierarchy. Instead a constraint rule is applied whose value represents the distance between the ends of the lines. The user language has a binary function *'on'* which returns the distance between its two geometric arguments, to assembly 'L2' and 'L3' the constraint rule is expressed as follows,

```
rule( l2:e2 on l3:e2 );
```

where the colon followed by *e1* or *e2* denotes either the first or second end-point of the line. In order to satisfy this constraint rule, the system is allowed to alter the angle of rotation of the model spaces of the coupler and driven links. When the rule is applied then the correct assembly is obtained as in figure 5.6a, when the space of the crank link is rotated and the assembly of the other two links is performed at each stage (cf. Figure 5.6a). A step-wise simulation of the motion is obtained, incrementing the drive model space and reforming the assembly, as in figure 5.6b.

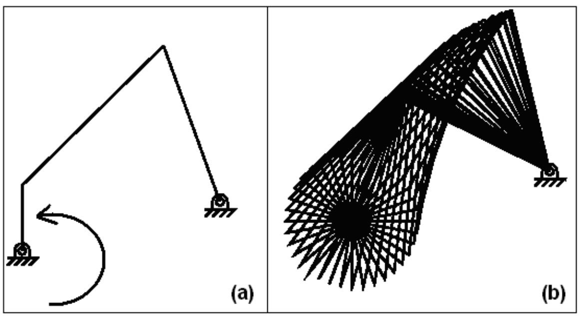


Fig.5.6. Motion of four-bar mechanism

When using this software in the modelling of machines, design constraints can be represented in two levels. One is termed *implicit*, where constraints are defined by construct procedures and parameters. Another is called *explicit*, by which constraints are defined by low-level geometric and topological elements (Wang, 2003). In general, the implicit constraints which relate to the hard constraints previously mentioned cannot be violated as these dictate the structure of the model e.g. the topologies of geometries. These constraints relate to function of a system. The explicit constraints (which relate to soft constraints) are the factors which will dictate the performance of the system (in this research).

The above classification of implicit and explicit constraints is generally true, although in this software it is also possible to explicitly model connectivity between all elements, although in practice this is not done. As identified in previous chapters an advantage of this software come from the employment of the constraints to connect higher kinematic pairs, such as rotary cams and gearing. As an example of the use of implicit and explicit constraints, consider the example below. The mechanism is a four bar linkage (cf. figure 5.7a). The mechanism is used as a transfer of bread based food products from one conveyor to another lying perpendicular to it. The transfer points are shown by the x's on figure 5.7b.

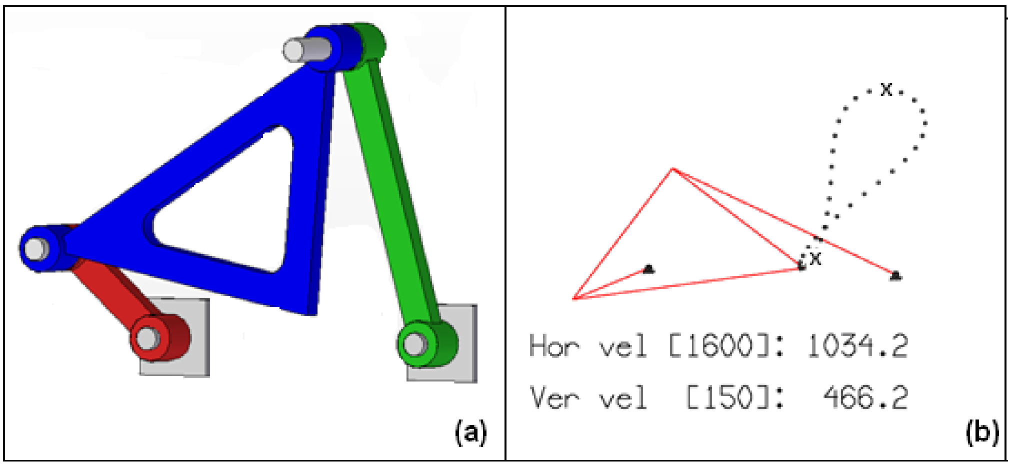


Figure 5.7 Transfer mechanism

The mechanism is constructed within the constraint modeller using seven entities and is assembled in a similar manor, to that in section 5.3. With the model constructed, the velocities of the mechanism motion are investigated (The results being shown at the base of the figure).

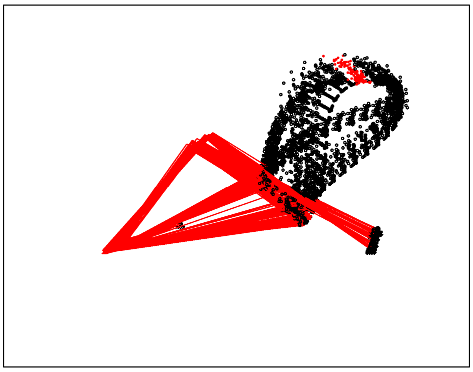


Figure 5.8 Optimization process

The explicit constraints are employed to produce required velocities at these specific points. These being 1600mm per second in the horizontal and 150mm per second in the vertical. To allow the modeller to achieve these values, the dimensions lengths for the five links in the model are permitted to be changed. Overlays of the modeller performing this operation can be seen in figure 5.8. The optimum results for this process can be seen in figure 5.9.

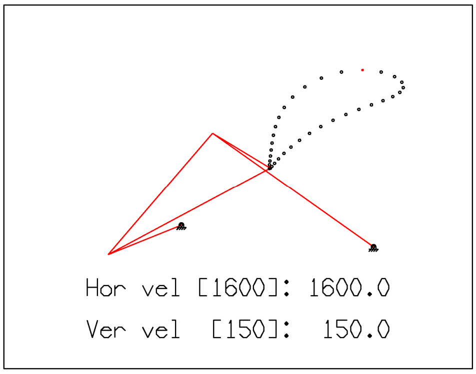


Figure 5.9 Optimal result

5.5 CONSTRAINTS IDENTIFIED

The emphasis for this research is functionality and performance. So, when simulating and modelling the processing equipment with methods such as that presented in Matthews (2006b; c) and Huda and Chung (2002), and while performing the study mentioned in section 4.1. What has become evident is that there is a group of seven generic implicit constraints that have to be handled within any modelling approach for machine and mechanisms that are employed for the processing of products:

• Displacement	To much or insufficient movement of elements of the mechanism, to translate required motions.
• Kinematics	The three time derivatives of motion.
▪ Velocity	Low or high velocities can cause timing problems
▪ Acceleration ▪ Jerk	Excessive acceleration and jerk cause vibrations, lack of accuracy and advanced wear.
• Dynamics	Effects of forces on the motion, increases in speed and product load can cause vibration, increased equipment wear and lack of accuracy.
• Design Rules	There are certain design laws, such as transmission angles that negate mechanisms from working effectively, that should not be violated.
• Part Interaction	Clash interaction between elements of equipment and the product being process.
• Incorrect construction	This is specific to modelling approaches that use rule based strategies for their modelling and simulation. As models are constrained to assembly and satisfy the given rules. The outputted assembly may not be the same as the object being modelled. An example of this is commonly seen with the four bar machine, the machine can assembly in an alternative manner even though as far as the modeller is concerned the constraints are met.
• Mechanism deconstruction	Motion causes elements of equipment to 'pull' apart.

These failure modes are represented by an Ishikawa diagram (figure 5.10) which allows specific examples to be assigned to each mode.

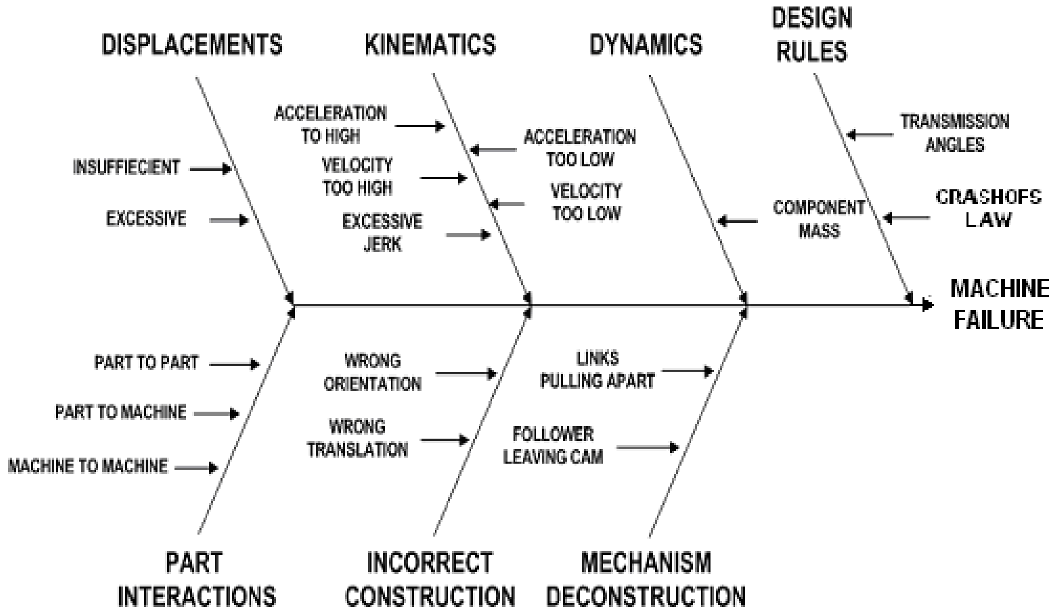


Figure 5.10 Machine failure modes (Matthews, 2007a)

The Ishikawa diagram is a good way of presenting the seven limiting factors to be considered in the modelling, as individual example of the limiting factor can be assigned to there respective limiting factor. From this point forward in the thesis, these limiting factors will be defined as the failure mode constraints.

5.6 CHAPTER SUMMARY

This chapter has described the constraint modelling software package which has been employed in this thesis. It reiterates from chapter 2, the main advantages this software gives for the modelling of machines for the identified problem in this thesis. It shows the process in which machines and sub-assemblies of machines can be constructed within the modelling environment, specifically the use of hierarchy of model spaces. It also identifies several generic form of machine failure.

The next chapter explains the processing evaluation and show the relationships between the relationship constraints, and how the constraints of product and process are employed to construction the maps of performance for the given machine.

Chapter 6

Machine processing and product variation

"I sometimes ponder on variation form and it seems to me it ought to be more restrained"
Johannes Brahms

This chapter explains the understanding required, and principles for the investigating the capability of the machines to process variant products. The chapter describes the relationships between the constraints of product and process which were defined in chapters 4 and 5, and how the relationships allow the engineer to understand and visualize the processing capabilities. To this extent the chapter explains the production of performance and opportunity envelopes of a machine system, and presents an extension to these, that allows the engineer to have greater understanding of which constraints are restricting a potential design solution. This takes the form of failure mode maps (FMM). The work described in this chapter concludes previous research on objective 3 and presents work for objective 4, from chapter 1.

6.1 CONSTRAINT RELATIONSHIPS

Table 6.1 Food product taxonomy

	Liquid	**Paste / Slurry**	**Particulate**	**Solids**	
				Rigid body	**Soft body**
Examples	Milk Soft drink Beverages Soups	Yogurt Fish pastes Yellow spreads Toothpaste Jams	Coffee Sauce granules Tea Cake mixes pasta	Chocolate Cookies Frozen-vegetables	Bread Cakes Meats Jelly

Key to any approach for the investigation of processing variant products is the understanding the relationships between the constraints of the product and process in combination. Continuing to use food stuffs as an example, investigation into the raw product that the food industry processes shows they can be categorised into five forms: liquids, pastes and slurries, particulates and solids, both rigid and soft bodied. Examples of products that fit into these categories can be seen in table 6.1.

Table 6.2 Product constraint relationships and types

FOOD PRODUCT PROCESS RELATIONS			
Type	**Product properties** **(limiting factors)**	**Relationships**	**Process effects**
	Weight		
	Density		Machine component
Liquid	Viscosity	Geometric	
Paste/ slurry	Geometric size	Volumetric	Speed
Particulate	Tolerance	Kinematic	
Solid	Shape	Dynamic	Capability
-rigid body	Strength	Timing	
-soft body			

Table 6.2 shows a relationship table for incorporating the taxonomy of food stuffs from table 6.1 and the limiting factors identified in chapter 4 (column two). Investigations have shown that these limiting factors present a generic range of relationships when considering the processing capability for variant products (Matthews *et al,* 2007a), as those shown in column 3, these are the factors which influence the operation of the machine. These also relate to the

machine modelling constraints identified in chapter 5. Column 4 presents the processing effects when considering the equipment.

The processing effects are the important factors for the manufacturer when investigating processing of product variants. Therefore, when visualizing processing capability, parameters relating to these should be mapped, such as machine components changes against processing speed. Figure 6.1 shows the relationships mapped onto a diagram when considering an example of changes for a particulate product: gravy granular production.

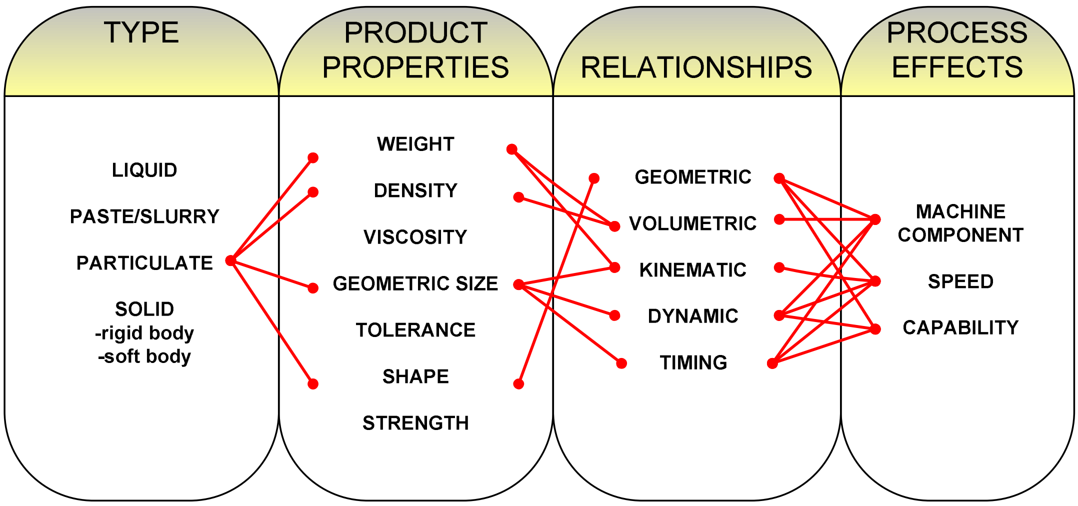


Figure 6.1 Particulate variation

For another example, a rigid body solid, a chocolate bar in a packaging operation, the relationship diagram would look as in figure 6.2. What this shows is there are connectivity's between product properties and process effect via the relationships. There for, any modelling or simulation must have the ability to investigate and monitor these relationship factors.

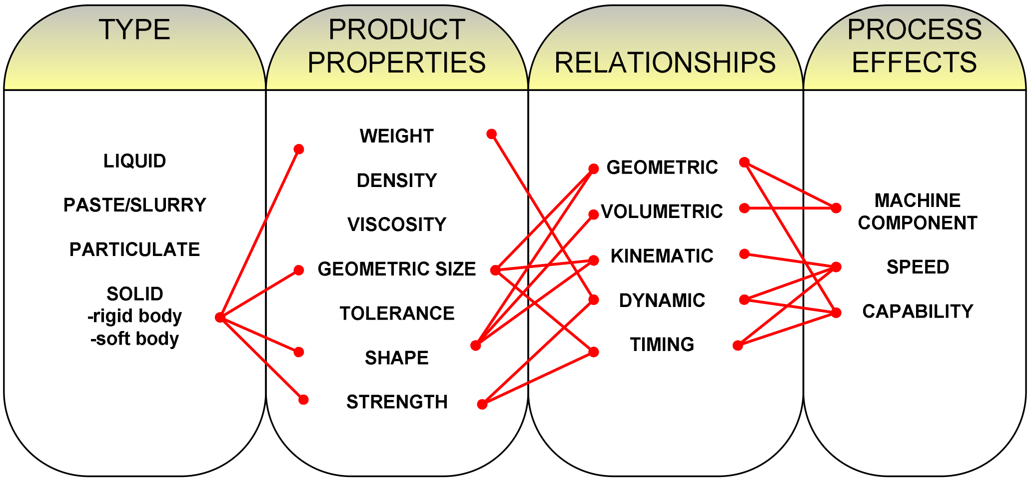


Figure 6.2 Rigid body product variation

6.2 PERFORMANCE ENVELOPES

Industries such as electronic component production and food processing tend to purchase special purpose equipment to process a specific product. This equipment may have inherent flexibility to cope with limited product variation, although concerns about initial costs restrict manufacturers in purchasing potential flexibilities in new systems (Jordan and Grave, 1995). When considering machine capability, the *envelope of performance* (cf. Figure 6.3) is the area where the machine will function, using only the inherent design adjustments. This envelope has also been termed as the capacity and capability envelope (Shewchuk and Moodie, 1998). This thesis introduces a new definition, the *envelope of opportunity* (Matthews *et al,* 2006d). This is the area where the design will function after external modification to configuration. The approach presented here not only allows the user to analyse the inherent flexibility of the system, but also allow the user to investigate the total envelope of opportunity.

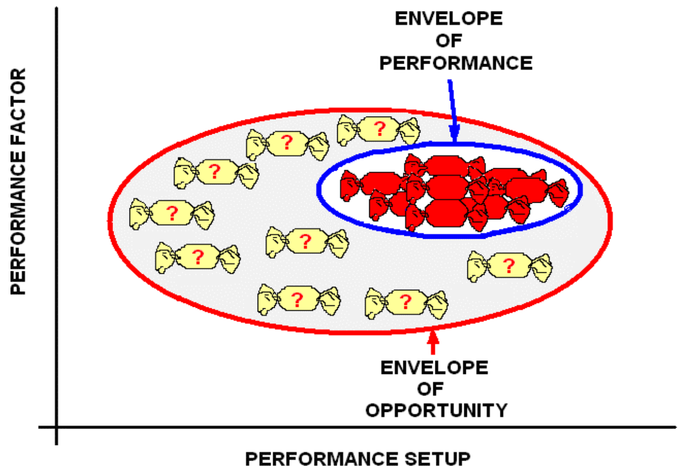


Figure 6.3 Performance and opportunity envelopes

Skewchuk and Moodie (1998) identified three approaches to cope with product variation. The first is to utilize the internal ability of any given system configuration to take alternative corrective action. This could be done by relaxing tolerances on component machine interaction points. Here, the approach does not modify the envelope of performance. If the change is too severe then the second is that the adjustment must be made to the internal capabilities of the system. This could be performed using adjustments inherit to the design, but as with the first approach, does not change the envelope of performance. Thirdly if the system cannot cope with the change by utilizing the first two options then changes must be made externally. This would involve shifting the envelope of performance. Investigations into this third option have identified this has to be sub-divided further to gain an understanding for the adoption of any new approach. In this event the Skewback and Moodie's definition has been split into three options (Matthews *et al,* 2006d).

1. Engineers can either look at ways to develop the flexibility of the existing design so it can cope with the variant product, that is increasing the performance envelope, as with figure 6.4a, this gives the envelope of opportunity (cf. figure 6.3) the total flexible range of the system, or,

2. More drastically the performance envelope can be shifted to encompass the new product, changing its configuration, but not giving the flexibility to produce the existing products moving from x on figure 6.4b to y, or

3. The system can be designed, so that *change parts* can be employed to reconfigure the design, and hence allow the design envelope to encompass the new product. This moves from x on figure 6.4b to y, but leaves the option to move back to x.

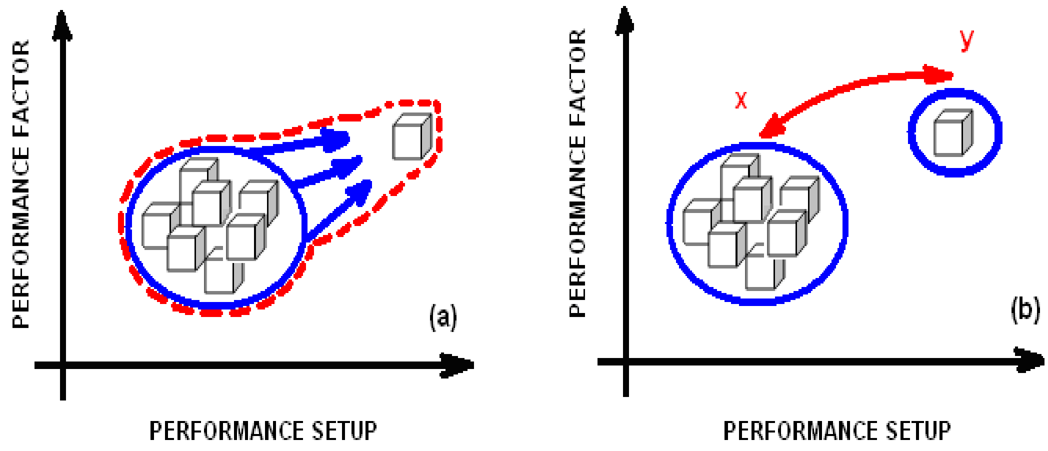


Figure 6.4 Processing capability change

6.2.1 Processing capability envelopes

This section explains the process of map construction. For this purpose a purely geometric failure mode example of a four bar linkage is used (figure 6.5). The approach is to firstly construct a parametric model of the mechanism within the constraint modelling environment. Figure 6.5b shows such a model, for the four bar linkage. The model has been constructed using the methods described in chapter 5. The mechanism is driven by the rotation of the crank on the left around it base pivot. The modes of failure for this mechanism are taken to relate to the path travelled by the point offset from the coupler. Failure is deemed to occur if the path passes outside of the rectangular box shown in the figure or if the mechanism fails to assemble or disassembles in operation.

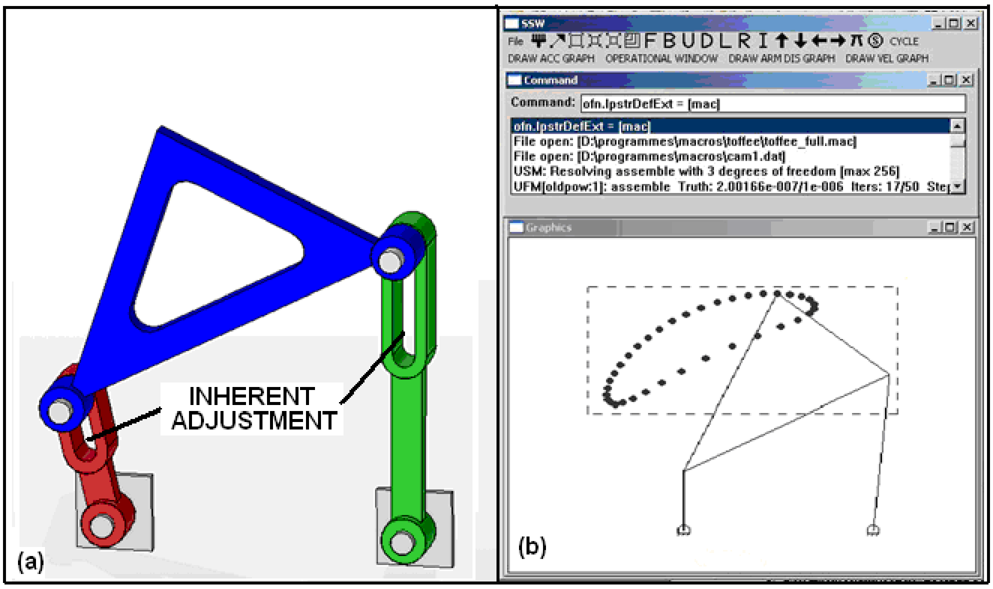


Figure 6.5 four bar linkage

Envelope of performance

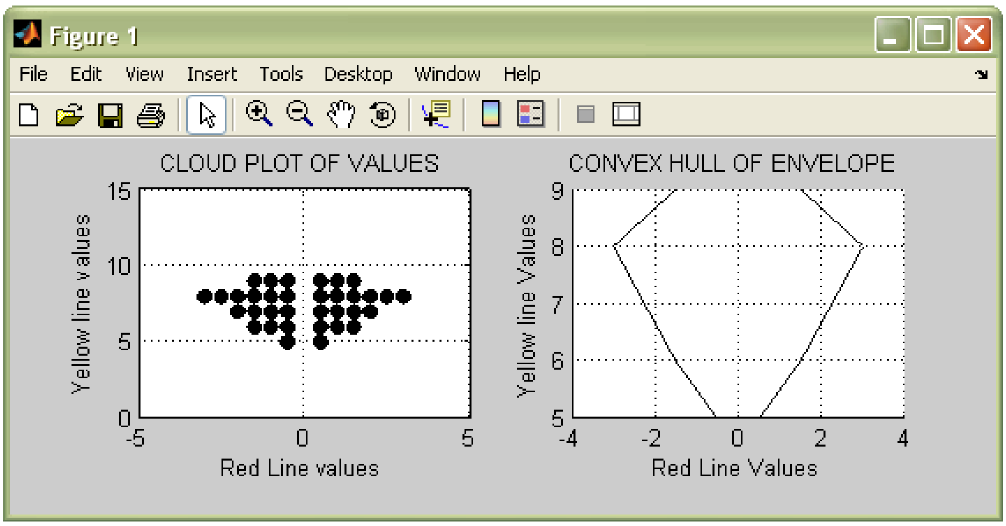


Figure 6.6 Performance envelope of mechanism

To produce the envelope of performance, the process starts with the parametric model produced; the inherent flexibility of the mechanism is investigated. The approach takes the known working model and 'disturbs' the design until it reaches the failure points. The factors which were allowed to change, are the lengths of the driven and crank links, and were bounded to the dimensions of the slots. The model is then run to check if this variation operates correctly. All correctly functioning instances was recorded, giving the envelope of performance for the system (cf. figure 6.6). It may be at this stage the system shows the functionality to process the variant product.

6.2.3 Envelope of opportunity

The next step is to investigate the envelope of opportunity. The process is identical to that of the envelope of performance, except the variables are either totally unbound or bound to the footprint size of the equipment. The variables can be changed automatically and the model is then run until the mechanism reaches the predefined goal of performance. These are automatically searched by routines within the constraint modeller, this is constraint satisfaction. When the mechanism runs without violating a failure mode, the configuration is recorded. The modeller selects the next start point and repeats the process. Figure 6.7a shows the envelope of opportunity for the mechanism, with figure 6.7b showing the combined envelopes. This approach has been labelled "limits modelling" (Matthews *et al* 2006a).

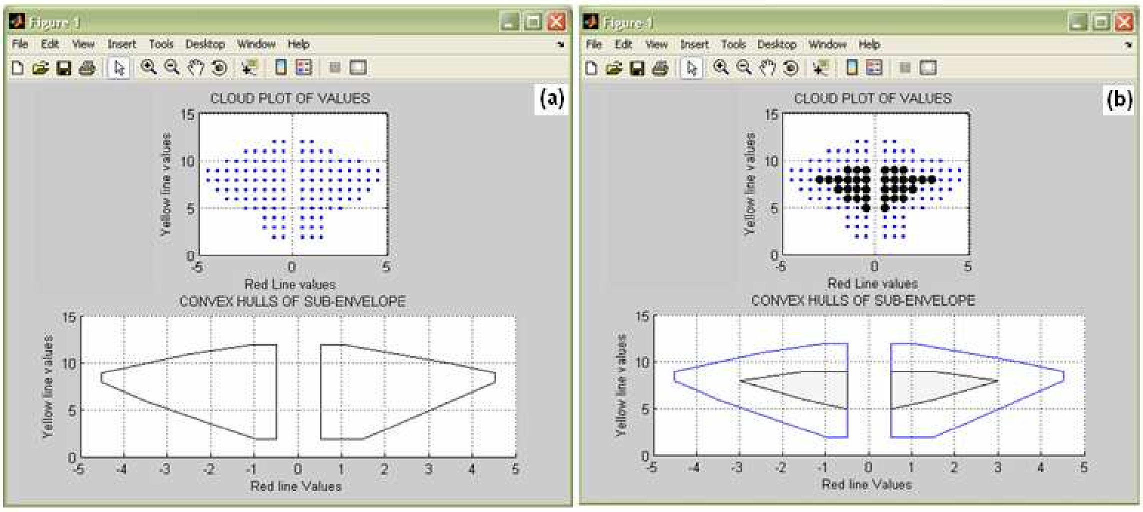


Figure 6.7 Capability envelopes of mechanism

6.2.4 Failure mode maps

The envelopes presented earlier in this section give the engineer a map for which the mechanisms function under defined performance requirements. Contemporary research has implied the benefits of learning from failures in product design (Petrosky, 2006). When redesigning a system and it works first time, then the only knowledge one has is the success. If the design fails it is possible to derive information from this failure: what the failure mode(s) are, and/ or which variable or cluster of variables in the system, is causing the failure. Learning from these are the stepping stones for the next iteration of the design activity.

Failure mode maps (FMM) are commonly employed in engineering science to graphically illustrate failure regions of properties, and as materials under given conditions. Examples of such maps can be seen in figure 6.8.

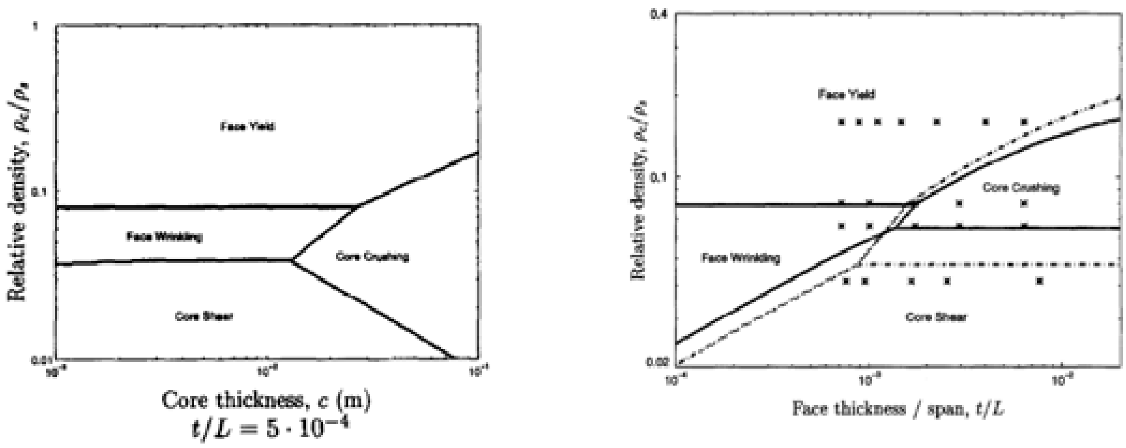


Figure 6.8 Example failure mode maps (Lim et al 2004)

Such maps have been employed by previous researchers. Bull (1997) produced FMMs for scratch adhesion tests for hard coatings. The maps were produced in terms of substrate and coating hardness. Trantafillou *et al,* (1987) used failure mode maps, defined for foam core sandwich beams, to design minimum weight beams for a given strength. Lim *et al,* (2004) produced FMM's for the impact and static loads of foam core sandwich beams. They stated the FMM was employed to avoid specific failure modes or achieve minimum weight design. Petra and Sutcliffe (1999) expanded on previous work of Bull to produce FMMs as a design tool for the production of honeycomb sandwich beams. In conventional FMMs as described previously, the whole map area includes is dissected by the failure modes. The maps presented in this thesis relate to mechanism and machine design. They also dissect the design space. They also converge on areas of functionality where the mechanism can be altered with no failure being invoked.

The generation of FMMs allows the designer to assess which failure modes are restricting a solution variant. With this knowledge the designer can assign the variant to a functional area where the failure mode is not violated. The approach used here requires the generation of a parametric model of the machine under investigation. The failure modes for the mechanism are investigated individually. Suitably chosen elements from the mechanism are disturbed (adjusted) and the effects explored. Once all start points have been selected, the next failure mode is selected and the process repeated. The output from the process produces a map of the failure modes. The combination of the boundary of the failure modes gives the functional limits of the mechanism.

The FMMs can be plotted individually and overlapping. These can then be simplified by removing failure modes which are not invoked because another failure mode has precedence. The FMMs can then be used to create a strategy to modify the design of the machine to allow for expected variation to an acceptable region of performance that is acceptable. The approach described in this thesis is demonstrated through the example of a four bar mechanism as section 6.21 and 6.22. Figure 6.6 has shown the working regions of the mechanism before the lengths of the driven and crank link cause the mechanism to fail to assemble geometrically to becomes disassembled at some point through the motion of the mechanism or assembles in the wrong mode that a configuration different to original constructed. A line which runs through zero on the drive crank axis, is produced, as the mechanism does not function if the crank length is zero. Such lines will also appear for in the FMM for *stationary configurations, dead centres and change points* in mechanisms. It is important to note, that using convex hulls to produce the envelopes, losses such information.

For the failure map construction each of these failure modes is activated individually and the envelope product process is followed as in section 6.2.1. Figures 6.9 and 6.10 shows the individual failure maps for the specific failure mode associated with the mechanism box, with the white zone being the failure areas and the grey being the areas of success.

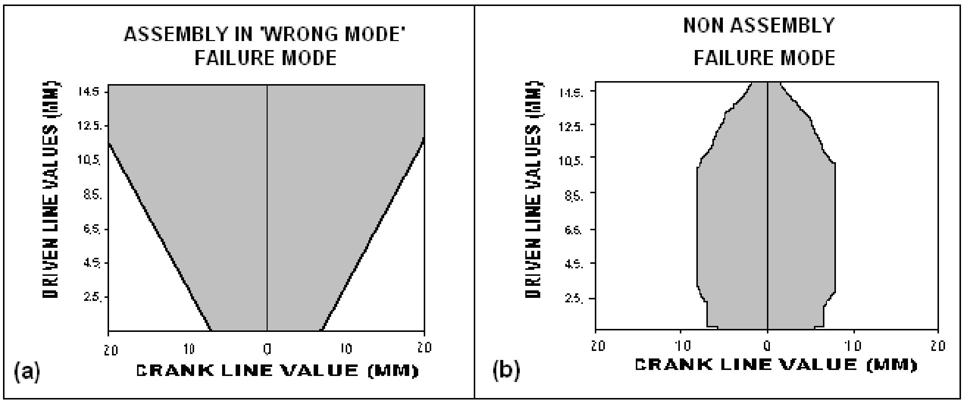


Figure 6.10 Mechanism 'non assembly' and 'assemble in wrong mode' failures.

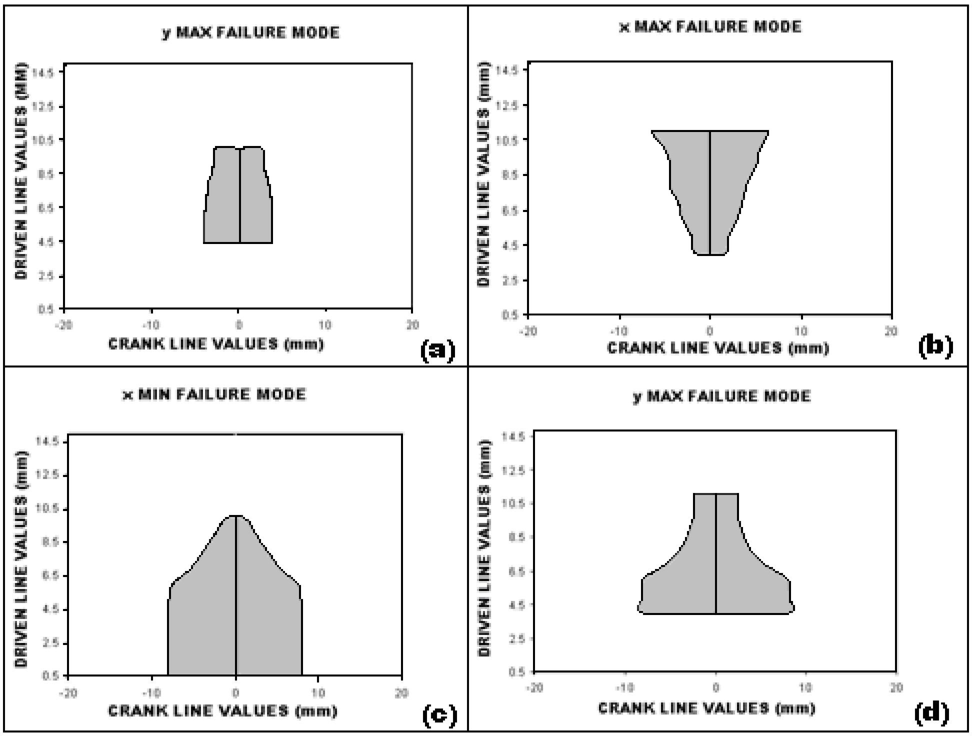


Figure 6.10 Box failure mode maps

What becomes evident when assessing such a simple mechanism against failure modes is how complex the failure assessment actually is. When all the failure modes are combined together (figure 6.11a), one can see the failure area where changes to these two elements means the mechanism will not function. With all FMM overlaid, the next stage is to remove un-invoked failure modes. In figure 6.11b these are mechanism collapse and deconstruction. The points of overlap can be identified against individual FMMs. The result of this process is can be seen in Figure 6.11b.

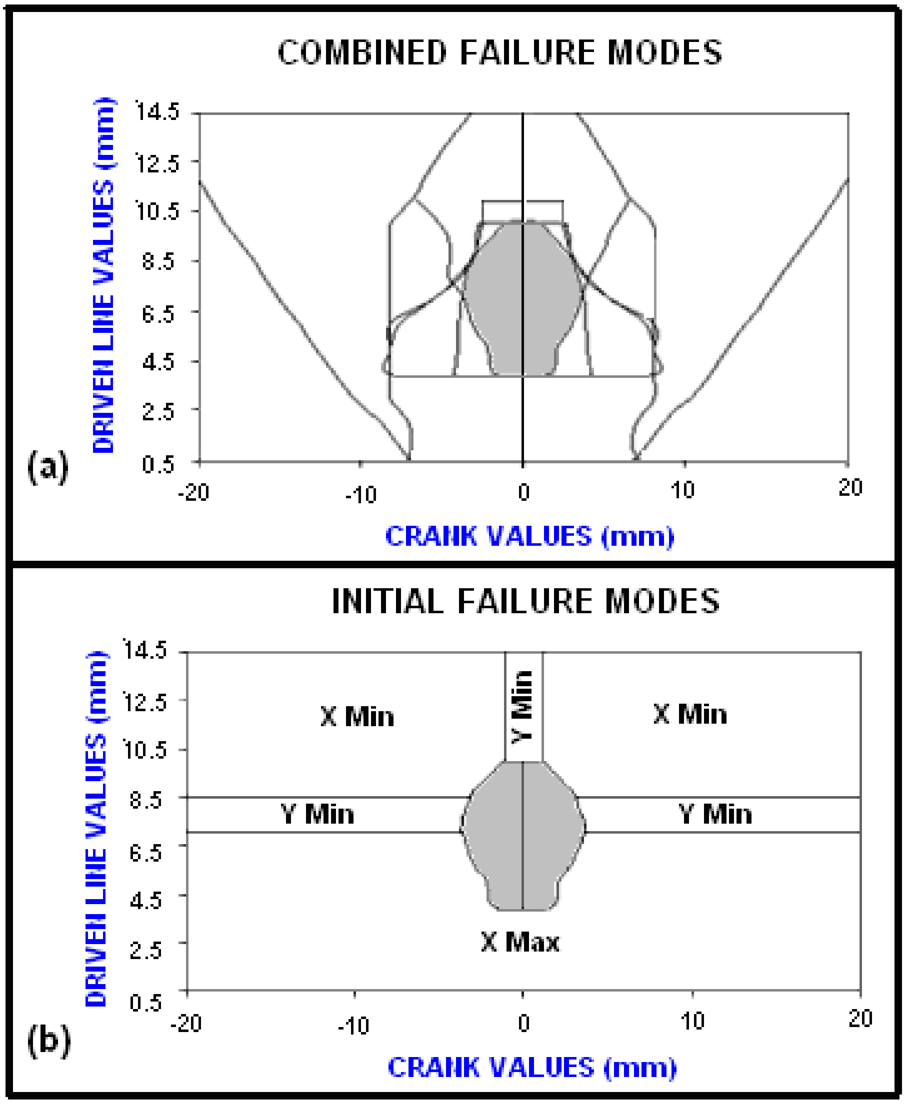


Figure 6.11 Failure mode maps overlapping

6.3 CHAPTER DISCUSSION

The work described in this chapter concludes previous research on objective 3 and presents work for objective 4, from chapter 1. For this objective the chapter has presented the understanding required, and related principles for the investigating the capabilities of the machines to process variant products.

The chapter has shown the relationships between the constraints of product and process which were defined in chapters 4 and 5, and how the relationships and their influences, allow the engineer to understand and visualize the processing capabilities. To this extent the chapter has explained the concepts and production of performance and opportunity envelopes for a machine system (Matthews *et al*, 2006d), and presents an extension to these, that allows the engineer to have greater understanding of which constraints are restricting a potential design solution. This extension takes the form of failure mode maps (FMM).

The next chapter amalgamates the work presented in this chapter and chapter 4 and presents an approach whereby this information can be applied to analyze an existing machine for its capability to process a variant product.

Chapter 7

Implementation strategy

"With lots of good ideas, implementation is the key, and so we need to keep our eye on the ball as we go forward"

Mitchell Reiss

The previous chapters have defined the need for the proposed approach and explained the reasons why a constraint-based method has been chosen. It has also explained the relationships between the constraints from both the machine and the product. This chapter builds on the previous chapter and describes how the constraint-based approach to finding the performance and opportunity envelopes of processing machines has been employed and implemented. The process can be divided into eight steps; these are described in the following sections. With this class of problem, one of the most critical aspects is the identification and formalization of a set of requirements for the new product with respect to the capabilities of the existing configuration. This often involves full production trials with the existing machine and specific testing and measurement of the new product. Once the requirements are established, constraints can be formalised for the design problem, and the investigation can start. This set of initial constraints is embodied in the existing configuration. This chapter presents work that fulfils key objective 5 from chapter 1.

7.1 STEP 1: PRODUCT PROCESSING CONSTRAINTS IDENTIFICATION

Each product and its preparation or assembly process demands different characteristics in order that it can be produced and handled successfully. Due to the handling and transfer processes involved, the strength and resistance to damage or movement upon on the machine, for example a conveyor belt, may need to be assessed. Many of these characteristics need to be determined and studied if the capability of the plant to handle such product is to be understood. The information is collected via experimentation using relevant testing equipment. Some products, such as foodstuffs differ from most commercially manufactured products in the fact, that it is solely customer *perception* of product that matters. Customers' views of quality come from their senses, manufacturers employ taste and smell panels, to assess quality and define the constraints (Fisher *et al,* 2005).

Additional to any customer defined constraints on the product, the prior research documented in chapter 4 identified seven generic product feature constraints: weight, density, viscosity, geometric size, tolerance, shape and mechanical properties, which most be tested on the product and their bounds found to define the processing constraints. For example, the motion limits permitted on a frozen Yorkshire pudding product before its casing deforms. The product is frozen batter mix, which is contained in an aluminium foil case. Figure 7.1a shows a product transfer; presently performed manually. The manufacturer (Tryton foods) would like to stack the product at this stage. The complexity comes from three variants of foil base (cf. figure 7.1c), and a variety of stack heights.

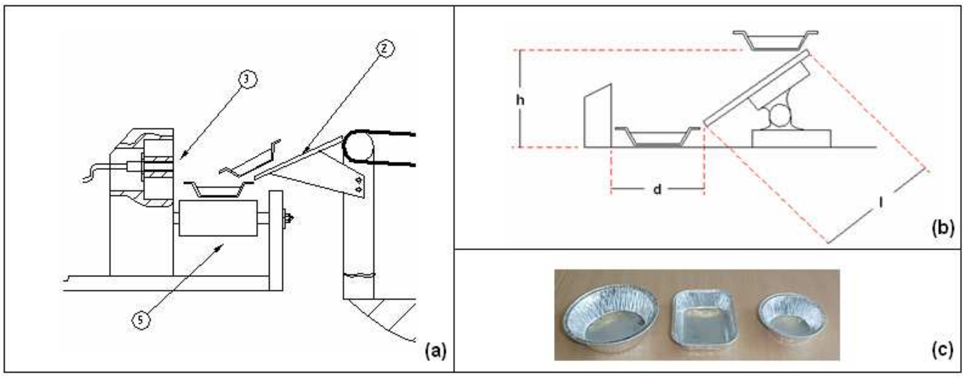


Figure 7.1 New process reconfiguration

Figure 7.1b shows a simple test rig that was used to investigate the stop length, height and length of chute and the chute angle in respect to damage of product during packaging. Tables 7.1 and 7.2 show just some of the results. The '*na'* for the large product relates to its dimensions being larger than that of the distance or height, the product must fit into. These have to be fed back into the model as geometric constraints.

Table 7.1 Stop variation

Distance(mm)	Large	Small	Square
70	na	x	x
75	na	x	✓
80	na	✓	✓
85	na	✓	✓
90	na	x	✓
95	na	x	x
100	na	x	x
105	✓	x	x
110	✓	x	x
115	✓	x	x
120	✓	x	x
130	x	x	x
140	x	x	x

Table 7.2 Chute height variation

height(mm)	Large	Small	Square
25	na	✓	✓
30	✓	✓	✓
35	✓	x	✓
40	✓	x	x
45	✓	x	x
50	✓	x	x
55	✓	x	x

7.2 STEP 2: ESTABLISH, VERIFY AND VALIDATE THE MODEL

The physical measurements of the system are recorded in combination with high speed video footage of the equipment operating. The machine is then parametrically modelled using the constraint modelling package, as described in chapter 5. Constraint satisfaction techniques are employed in the construction of the model. The resultant model is first verified and validated, then tested for its appropriateness for investigation process.

The validation of the model is the process of making sure the model represents reality, whereas the process of verification identifies that the model operates as the designer or customer intends. In this approach, it is generally been performed by comparing its function against the high speed video footage of the system. Full validation of the model is important as the model presents data upon which judgements relating to the redesign strategy are later based. The model is validated through comparison of theoretical/ prediction results with those obtained through experimental investigation. This step is very important, as it generates design knowledge and understanding of the existing design, assuming that this is not otherwise available.

7.3 STEP 3: DEFINE FAILURE MODE CONSTRAINTS

While investigating industrial examples, a study was undertaken to determine which factors caused machinery from the food processing and packaging industries to fail. The identified factors are shown in table 4.2 of section 4 and shown graphically in figure 7.2.

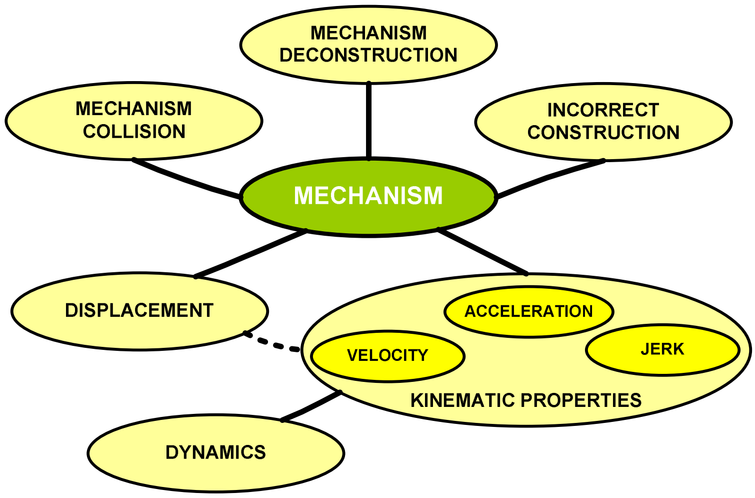


Figure 7.2 Mechanism failure factors

While investigating variation effects to systems, it was found that most of the failures occur with the equipment reaching its limit factors. Examples of these include: insufficient displacement achievable, required motions forces the mechanism apart, or accelerations are too high, inducing vibrations and wear. However product factors also affect the failure responses. For example consider a mechanical gripper and transfer mechanism from a piece of equipment producing a frozen product. Marketing changes now mean the customer is offering to product in a non frozen variant. This affects the mechanism in two ways: the package is softer, so less grip pressure can be applied and speed of transfer is limited due to potential deformation of product. For this reason the failure modes must be agreed with designers/ engineers along with some proper testing of product. The relationship diagrams presented in chapter 6 identify which failure mode constraints need to be modelled.

7.4 STEP 4: ASSOCIATE FAILURE DETECTION TO MODELS

This section introduces the tasks to detect certain forms of failure as identified in figure 7.2. Failures within the modelling environment have been categorised under three headings: the inability to assemble correctly, satisfactory motion and clash detection. Table 7.3 highlights the techniques employed within the modeller to identify these failures.

Table 7.3 Task to detect forms of failure

Failure mode	**Detection approach**	**Description**
Inability to assembly correctly	Truth maintenance	The modeller performs assemblies by minimizing the error in constraint rules which represent the distance between parts. Its ability to do this can be used the assess it ability to assemble and stay assembled throughout the motion.
Satisfactory motion	1. Bounding box 2. Point displacement & non-excessive kinematics	1. This is where a box contains an object throughout its motion. A check can be invoked to identify interactions between box produced by the motion of the object and another box defined as the expected motion for the object. 2. Model is defined within Cartesian space; the co-ordinates of each element within the model can be mapped while in motion. Conditional statements are employed to investigate maximum and minimum displacements. With motion initiated in the model, this ability is also utilised to calculate the time derivatives of motion.
Clash detection	Embedded solids	The constraint modeller has the ability to identify the volumes of solid objects. The change in volume is used to detect the interaction between elements of the model

In the approach constraint monitoring technique is employed to check for the failure modes identified in table 7.3

7.5 STEP 5: DISTRUB FOR INHERENT ADJUSTMENT

Within this research, the term “disturbance” implies the mean parametric variation of the variables defined in the model. These are used to find the successful instances of the model operating under the failure modes. This step is only investigating functioning points to find the inherent capability of the system. The adjustments and tolerances were noted in Step 2 of the approach. These adjustment and tolerance are now modelled in different configurations as noted in chapter 6. There are three strategies for the disturbance that can be performed within the modeller. The three strategies are as follows:

1. *Program modeller to disturb dimensions of model*: The variables within the model can be programmed to vary in dimensionality. A strategy for the disturbance has to be decided prior to this step.
2. *Set goal, and use the modeller's optimising function*: the internal optimiser with the constraint modeller can be used when a goal is set for the model (constraint optimization technique). The modeller will iteratively optimise the model; all successfully functioning instances can be recorded to produce a functional matrix.
3. *Design for experiment*: with the preliminary limits established for the individual variables, statistical software such as Minitab® (Barbara *et al,* 2005) or MATLAB (Mathworks inc, 2005) can be used to generate a test matrix of preliminary limits to be run through the model. Successful instances from the test matrix can be logged to produce the functional matrix. This is the preferred method statistical tools easily generate data for large quantities of variables that are associated with complex equipment

The resultant functioning points can be used to produce the envelope of performance.

7.6 STEP 6: DISTURB FOR POTENTIAL CONFIGURATION

Step 6 is required when the inherent capability of the system is not able to process the variant product. This step now requires that all elements within the system can be adjusted to find a solution, this employs the limit modelling To assess the initial potential for the machine to be adjusted, the user can also employ two inherent function within the modeller: bounded search and sensitivity analysis, these are described below:

- *Bounded search*. The search capability, of the modeller is employed to establish if the system modelled is within the global limits set for the system. Examples of such limits can be the geometric footprint of the machine, or cost factors. This gives a crude investigation, showing if the mechanism has functionality and is appropriate to undergo the limits modelling process.
- *Sensitivity analysis*. This is the procedure of incrementing design parameters and examining the relative changes in model response. When smalls change in a parameter of a system result in relatively large changes in the outcomes, the parameter is deemed sensitive. This information is then used to decide which, are the important parameters to investigate, during the limits modelling.

The adoption of bounded search or sensitivity analysis lies with the engineer/ designer. The outcomes of the limits modelling approach, is a crude sensitivity analysis in its self. The bounded search generally is used to restrict the initial search space; this can have implications on the production of failure mode maps.

7.7 STEP 7: EVALUATE AND REPRESENTATION OF RESULTS

Steps 4 and 5 result in a list of successfully functioning points these are recorded individually to form the morphological matrix. A partial example of a morphological matrix is shown in table 7.4 This matrix is the first form of representation of the functional points comes, which can have the performance factor associated with them. It can also be useful to have the data from the matrix in a more graphical representation. The following are some of the options which have been employed for different limiting modelling design exploration situations.

Table7.4 Example morphological matrix

EXCHANGE MECHANISM								
link1	link2	link3	pusher1	pusher2	camA1	V	A	J
26	31	110	12	56	75	3	3	0
26	31	111	12	56	75	3	3	0
26	31	112	12	56	75	3	3	0
26	31	113	12	56	75	3	3	0
26	31	114	12	56	75	3	3	0
26	31	115	12	56	75	3	3	0
26	31	116	12	56	75	3	3	0
26	31	117	12	56	75	3	3	0
26	31	118	12	56	75	3	3	0
26	31	119	12	56	75	3	3	0
26	31	120	12	56	75	4	4	0
26	31	121	12	56	75	4	4	0
26	31	122	12	56	75	4	4	0
26	31	123	12	56	75	4	4	0
26	31	124	12	56	75	4	4	0
51	56	149	27	81	75	7	7	0
51	56	150	27	81	75	7	7	0
51	56	151	27	81	75	7	7	0

- *Cloud plot:* is a multi-dimensional scatter-gram. The 2D and 3D variants of this of diagram are normally associated with statistical analysis and presentation of data and in the study of geophysical data. (Hocking, 2001). Additionally recently scatter-grams have also been used as a tool for linking scientific and information visualizations. In this work each line from the matrix relates to a point plotted on the cloud map. The cloud map gives a visual representation of the function space of the mechanism. The boundaries of the cloud map are the limit conditions for the mechanism / machine (cf. figure 7.3).

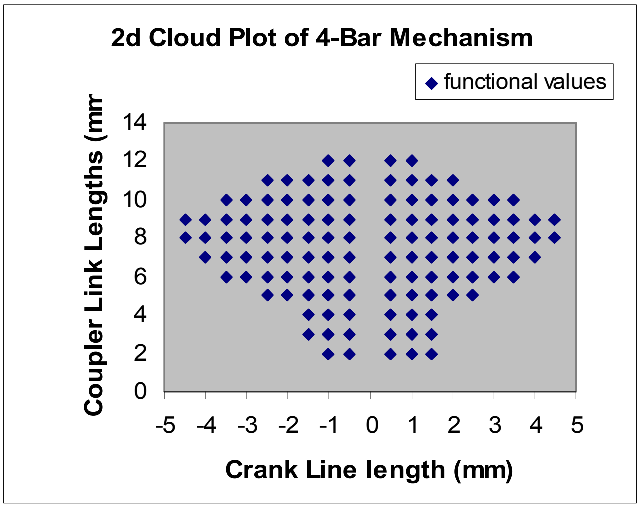


Figure 7.3 Example Cloud plot

- *Convex hull:* The convex hull (Shamos and Preperata, 1985) for a set of data is the minimal convex shape containing the given data. It is possible to produce a convex hull from the data plotted from the cloud map in MATLAB, it also allows the volume and surface area of the hull to be computed. When a new configuration is required and the new point is plotted into the data set, it can be compared with the original hull. If the volume or surface area has increased, then the new configuration lies outside of the limits of the mechanism. The use of the convex hull is suitable when the data set is large and closely grouped. Similarly convex hulls have been successfully employed in representing the configuration space of robot manipulators (Botturi *et al,* 2003). As with the cloud plot, the convex hull process can be extended to a range of machines for comparisons.

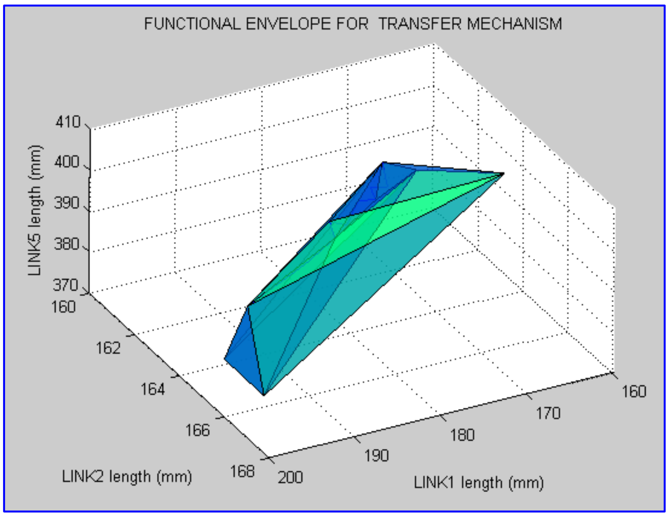


Figure 7.4 Example convex hull

- *Failure mode map (FMM):* (Matthews *et al,* 2007c). This approach has been created from the limits modelling approach. Effectively the approach is used to perform an exhaustive search of the design area against given setup, performance and function factors. The approach records points where the system functions correctly and where constraints are violated. These violations are recorded and plotted. This offers the user the potential to see the given boundary for the system and the constraints which limit any other development.

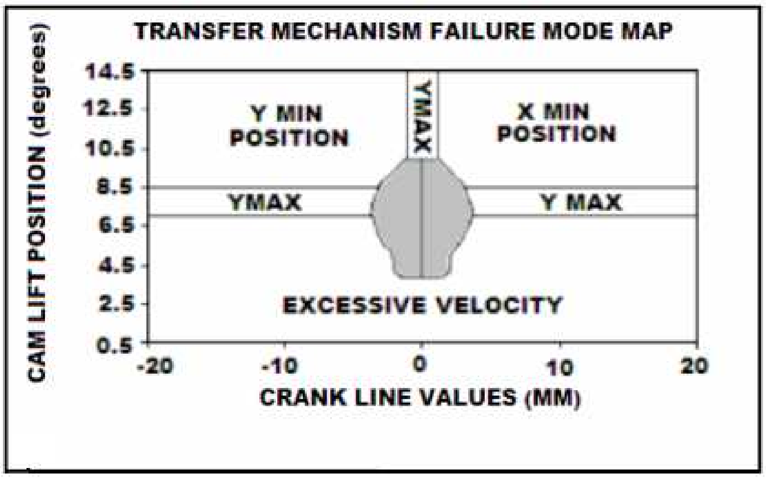


Figure 7.5 Example failure mode map

- *Surface plot*: a surface (Khuri and Cornell, 1987) can be fitted to the categorized data variables corresponding to sets of *XYZ* coordinates, for subsets of predetermined data determined and arranged in one display to allow for comparisons between the subsets of data. The limits modelling approach can be used as the investigation tool for a response surface methodology

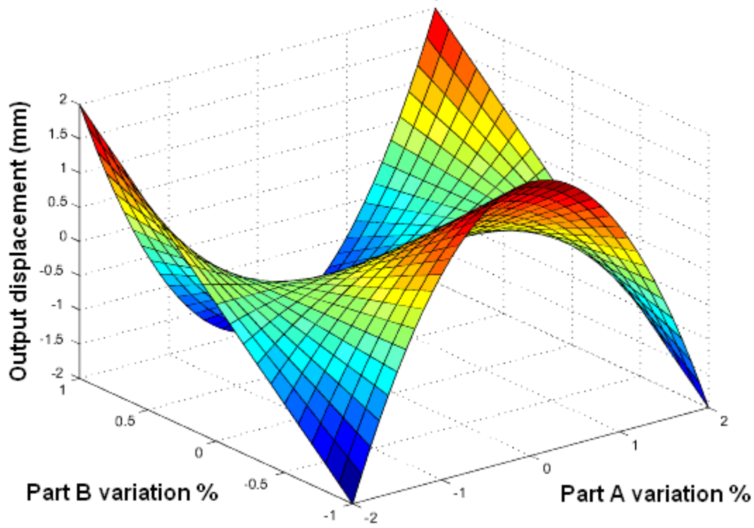


Figure 7.6 Example Surface plot

7.8 STEP 8: POTENTIAL REDESIGN STAGE

In most cases, it becomes obvious that there are, multiple configuration that will process individual products. At this stage the differing characteristics can be investigated simultaneously and compared against selected critical product characteristics. At this stage the designers and manufactures will have to evaluate which design solution they feel is best. Here a constraint-based optimization approach can be employed to find the optimal instance for the given product. It is also possible at this stage to reuse the modeller's sensitivity analysis function upon each configuration.

7.9 CONSTRAINT-BASED MODELLING APPROACH FLOWCHART

The steps presented in sections 7.1 to 7.8 are represented in the flow chart figure 7.7 following. This shows the concurrent start to the process i.e. the product and process constraint identification and then association to the overall model. The process then carries on in a linear nature with the design capability investigation(s)-steps 5 and 6. In the figure, the limits modelling approach (step6) is preselected as one process block.

The full approach is shown in flow chart figure 7.8. Once the data has been recorded, a relevant visualization technique is produced and critical areas of the design can be analyzed further. At this point, changes to the model can be investigated and potential new solution adopted, this leads to the detailed design and manufacture.

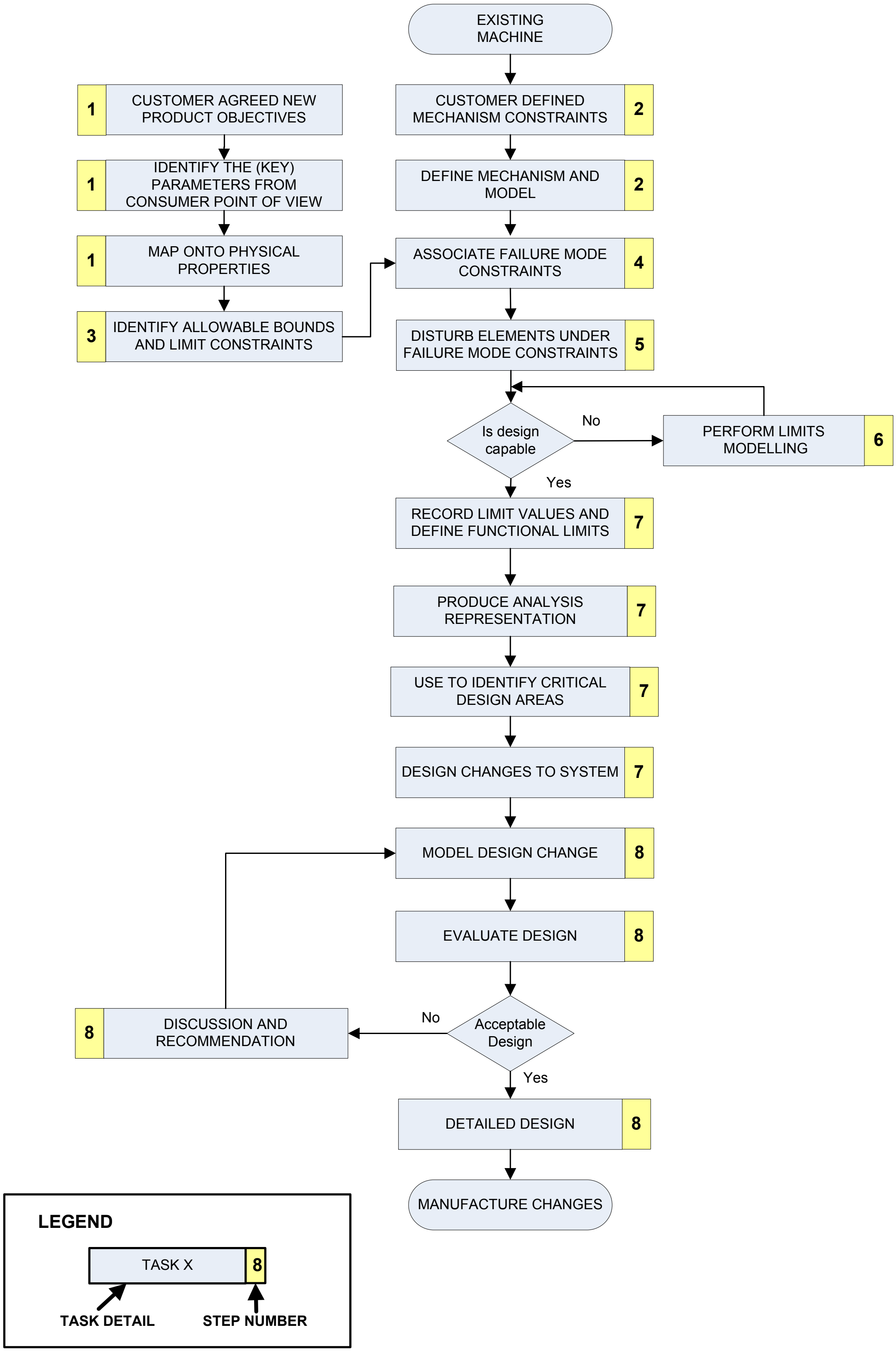


Figure 7.7 Modelling approach flowchart

7.10 LIMITS MODELLING APPROACH

Figure 7.8 presents the limits modelling approach sub-flowchart, noted in section 7.9.

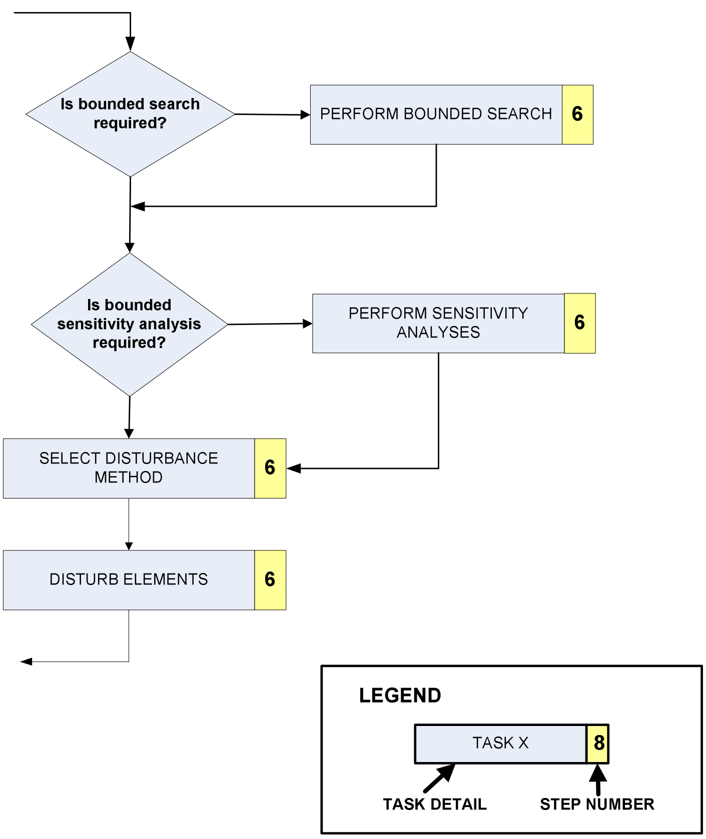


Figure 7.8 Limits modelling approach (Matthews et al 2006b; c)

7.11 CHAPTER SUMMARY

This chapter has presented the amalgamation of the techniques shown in the previous three chapters. These are formulated into a structured approach which has been presented in the flowchart figure 7.7 and figure 7.8. This chapter has fulfilled objective 5. The next chapter utilizes this approach and its constituent techniques to analyze the ability of three machines to process variant products.

Chapter 8

Industrial case studies

"The only relevant test of the validity of a hypothesis is comparison of prediction with experience"
Milton Friedman

The previous chapters have explained the theory behind the approach and the implementation strategy. This chapter present the approach applied to industrial case studies:

- *A confectionary packaging machine: where the producer would like to investigate the capability of the existing machine to process a larger product.*
- *An overwrapping packaging machine: where the producer has to pack a different product with a new packaging film.*
- *A case packing machine: where the producer wants to pack a different product into a new product into a new optimal pack configuration.*

For each case study the relevant constraints are identified, along with the specific handling technique: monitoring, satisfaction or optimization. The case studies have been chosen to show how different industrial problems can be handled using the approach. This chapter presents research that fulfils key objective 6 from chapter 1.

8.1 CASE STUDY 1: Ejection Mechanism

The following problem investigates the capability of a confectionary wrapping machine to process a larger product. This section describes the equipment, defines the problem and shows how the approach described in chapter 7 is applied.

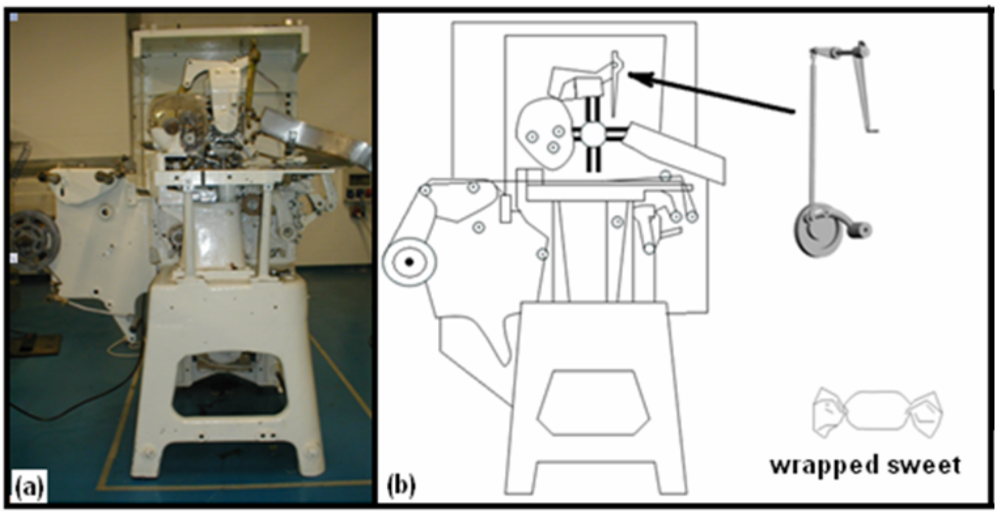


Figure 8.1 wrapping machine

8.1.2 STEP 1: Processing constraints identification

If the producer needed to wrap a sweet bar with dimensions of 20mm height, 70mm long and 40mm width, yet maintain the ability to wrap the original product, would it be possible? This would mean expanding the performance envelope in the nature shown in chapter 6. Preliminary investigations of other sub-mechanisms show an ability to process product of a height of 32mm, width 50mm and length of 83mm. The mechanism has topological hard constraints. A Geneva mechanism indexes the gripper jaws into a set position. The position of the pivot points for the cam follower and the pushrod to link are fixed. The length of the ejection arm is constrained, as the product is held centrally in the gripper jaws and the index position for ejection is fixed. For the purpose of this case study the cam profile is not evaluated for modification. This leaves the four links as the option to produce the configuration to process the new and old product.

8.1.3 STEP 2: Establish, validate and verify model

For this study, the physical measurements of the mechanism were recorded in combination with high speed video footage, such as that shown in figure 8.1c; showing the gripper jaws. Figure 8.2 shows the ejection mechanism modelled in the constraint modeller. The ejection mechanism comprise of a cam driven four bar chain with two fixed pivot points. The circular form at the base of the model is the drive cam. The cranked arm attached to the fixed pivot point and resting on the drive cam is the cam follower. The upright line is the pushrod. The link is the line spanning the top of the pushrod and the top fixed pivot point. The line descending from the top fixed pivot point is the ejection arm. The resultant model was then compared against the high speed video footage to verify the functionality.

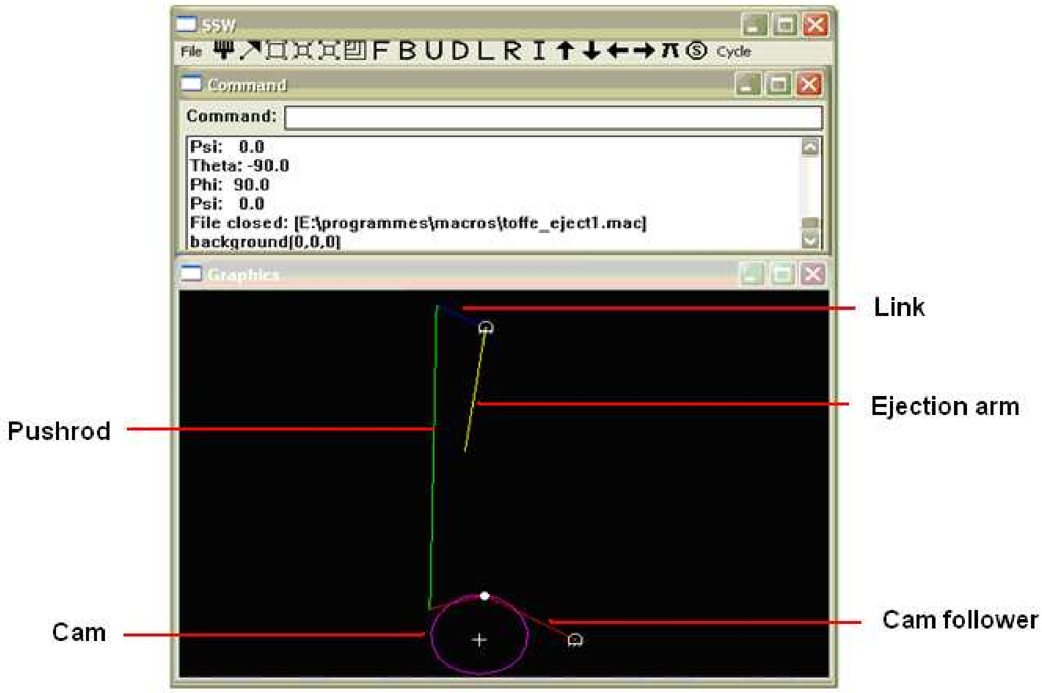


Figure 8.2 Initial model

As shown in chapter 5, the construction of models is performed using a hierarchy of *model spaces* and graphical entities, assembled using inherent functions of the modeller and constraint rules. The *model space* hierarchy for the ejection mechanism which was employed during the construction of the model shown in figure 8.2 can be seen in figure 8.3. Excluding the inherent constraint modeller function pivot and embedded *model spaces* within other spaces, two constraint rules are used to complete connectivity of the model:

```
Pushrod:e2 on link:e1
```

To connect the pushrod and the link elements,

```
Camfollower1:e2 on cam1
```

To connect the cam follower arm to the drive cam, these constraint rules are represented on figure 8.3, by the command "rule". Within the modeller constraint optimization is employed to maintain connectivity of the model.

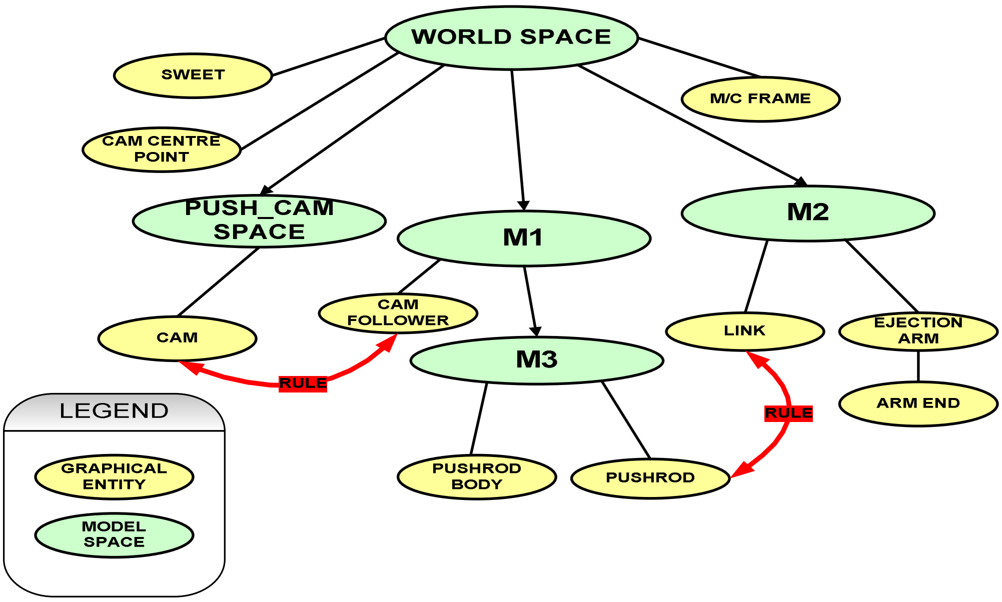


Figure 8.3 Model space hierarchies for ejection mechanism

8.1.4 STEP 3: Definition of failure mode constraints

While evaluating the relationships shape constraints do not come into play and the change in product weight is negligible and so not an issue for the mechanism. It is a single product so density constraints are not considered and, as the product is a solid, there are no viscosity constraints. But the change of product does give a geometric size constraint to be addressed. This only invokes the single geometric relationship to be modelled (cf. figure 8.4). This, in turn indicates that for the process effects, machine component parameters need to be presented in any visualization.

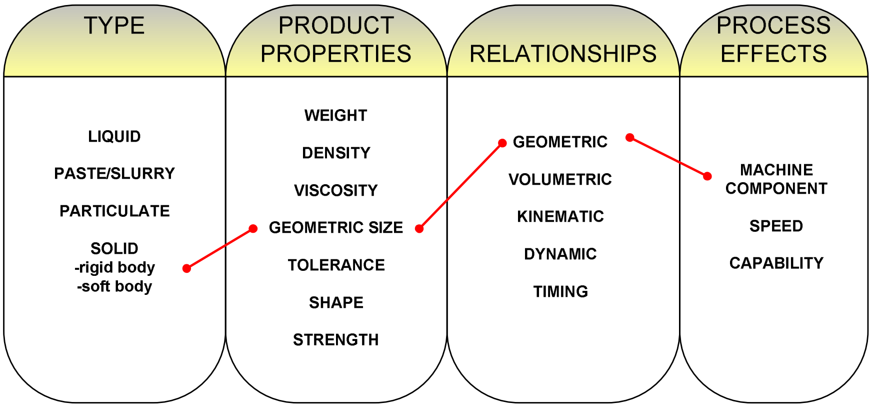


Figure 8.4 Relationship diagram

With the model produced and tested and the requirements and relationships for the model analysed (cf. figure 8.4), the next stage is to define the factors which stop the mechanism from functioning under the new product conditions. The following failure modes constraints were established for the ejection mechanism.

Table 8.1 Ejection mechanism failure mode constraints

	Failure mode Constraints	**Description**	**Association**
a	Mechanism Deconstruction	Breakages in mechanism	Machine
b	Collision	Pushrod interacts with frame of machine	Machine
c	Collision	Eject arm interacts with pushrod	Machine
d	Displacement & Collision	Ejection arm movement insufficient or incorrectly orientated to remove the sweet from jaws	Machine
e	Displacement	Ejection arm rest position too far forward	Machine
f	Displacement	Ejection arm max position	Machine

8.1.5 STEP 4: Associate failure mode detection to models

The initial model is drawn in wire-frame construction, but for the failure mode detection for ‘b, c, and d’ of Table 8.2, solids are embedded into the model. The solid elements (cf. figure 8.5) added to the model are the vertical rectangular and square block to the left, which models the machine frame. The rectangular block to the right of the model is the new sweet held in the machine jaws. The upright block on the pushrod is the body of the pushrod and the cylinder disc at the end of the ejection arm is used to check ejection arm contact to the sweet and pushrod. The inbuilt ‘*Truth*’ function is employed to detect mechanism deconstruction (a) and geometric positioning was used to detect maximum and minimum position and the velocity of the ejection arm (e and f). The full code for this model can be seen in appendix A. The constraint monitoring technique is employed within the program to check if any of the failure modes identified in table 8.1 have been violated.

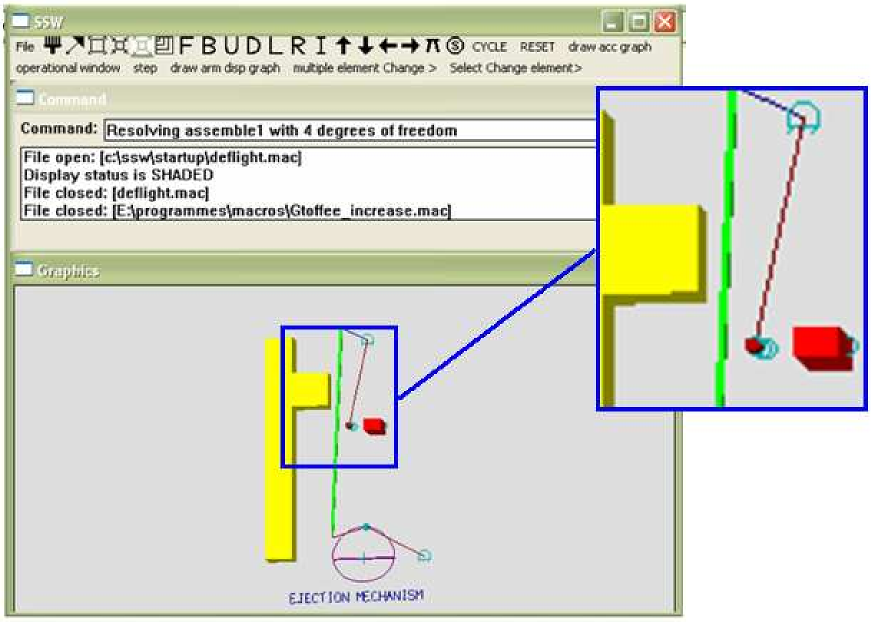


Figure 8.5 Constraint model of mechanism

8.1.6 STEP 5: Disturb model for inherent adjustment

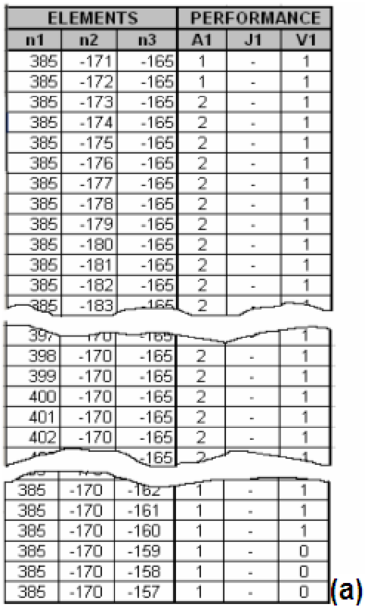
The initial model was run with the new product, and the inherent variation of the system modelled. The results of this modelling illustrated that the ejection mechanism interacts with the product while in its rest position. Therefore showing the design was not capable, and further investigation required.

8.1.7 STEP 6: Disturb for potential configuration

As the cam profile and ejection arm length were was not to be altered, this left the three remaining elements: cam follower arm, pushrod and link, as the elements for disturbance. The limits modelling approach presented in chapter 7.10, was applied.

8.1.8 STEP 7: Evaluate and represent results

The values from disturbance to the elements are recorded individually to give the functional matrix (Figure 8.6a). From the matrix a cloud plot is produced (figure 8.6b) in MATLAB, this plot is then used to generate the convex hull (opportunity envelope) shown in figure 8.7.



ELEMENTS			PERFORMANCE		
n1	n2	n3	A1	J1	V1
385	-171	-165	1	-	1
385	-172	-165	1	-	1
385	-173	-165	2	-	1
385	-174	-165	2	-	1
385	-175	-165	2	-	1
385	-176	-165	2	-	1
385	-177	-165	2	-	1
385	-178	-165	2	-	1
385	-179	-165	2	-	1
385	-180	-165	2	-	1
385	-181	-165	2	-	1
385	-182	-165	2	-	1
385	-183	[illegible]	2	[illegible]	[illegible]
397	[illegible]	[illegible]	[illegible]	[illegible]	1
398	-170	-165	2	-	1
399	-170	-165	2	-	1
400	-170	-165	2	-	1
401	-170	-165	2	-	1
402	-170	-165	2	-	1
[illegible]	[illegible]	-165	2	[illegible]	1
385	-170	-162	1	-	1
385	-170	-161	1	-	1
385	-170	-160	1	-	1
385	-170	-159	1	-	0
385	-170	-158	1	-	0
385	-170	-157	1	-	0

(a)

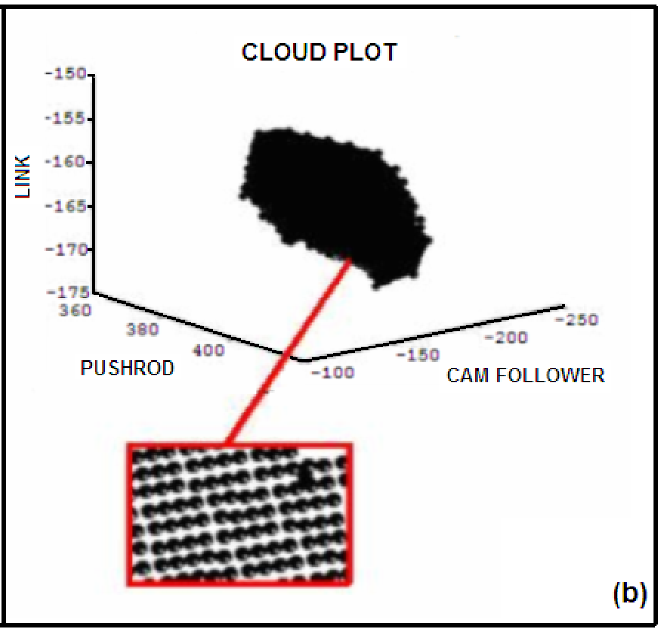


Figure 8.6 Matrix of functional points and cloud plot

Figure 8.7a shows the opportunity envelope produced for the original sweet, with the new sweet failure mode limits assigned to the model 8.7b is produced.

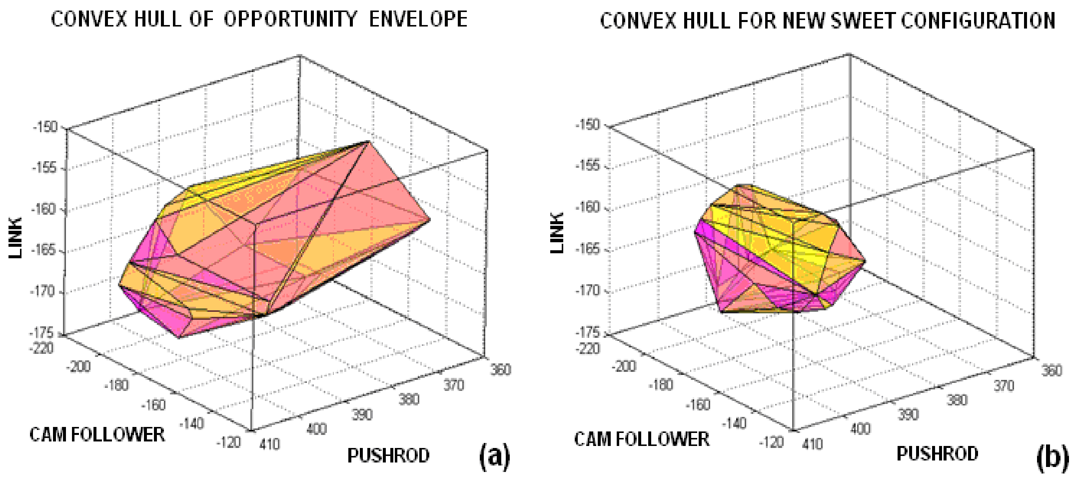


Figure 8.7 Convex hulls of opportunity envelopes

The parameters to produce the new failure mode specification were added to the model, these constrained the motion for both the old and new sweet. The envelope produced encompassed regions where both products could be produced. The fact that points can be plotted and a hull produced, indicates that a configuration exists that can produce both products, although the opportunity envelope is greatly reduced, and shown to be a sub-region of the original product's convex hull. By implication the system should be capable of processing all products that lie 'chained' (Jordan and Grave, 1995) in the product family in between.

To test this, two further products were modelled in the system: a product with a large width, that the mechanism should not be able to handle; and another product, with dimensions that lay half way between the new product noted in the problem section and the original product. The resultant hull can be seen in figure 8.8. Here the convex hull for the original product is also plotted. The approach shows that as the size of the product increases, the performance envelope decreases.

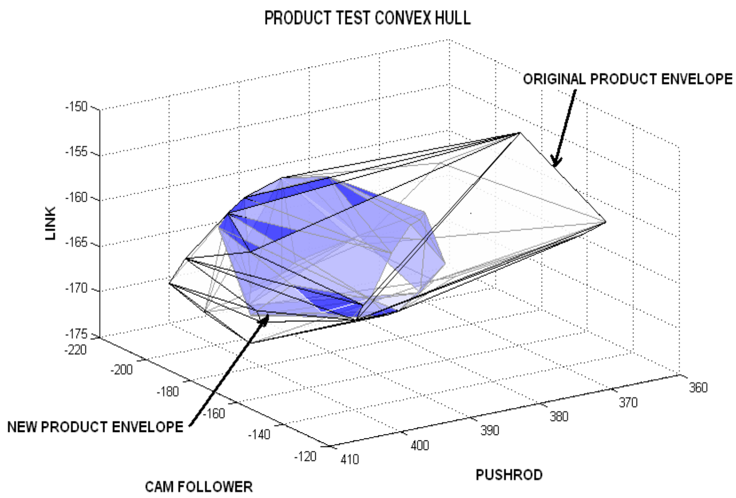


Figure 8.8 Test convex hull

The opportunity envelopes in figure 8.7 show the functioning areas for the mechanism. This, points to multiple configuration possibilities for a functioning system with the new sweet. The limits modelling approach also presents a basic sensitivity analysis, presenting the link elements as the most sensitive to change and to unbalance the operation of the mechanism. The pushrod appears as the least sensitive, and, for this reason, is the best option for the element to change to capably process the new product. If a reduction adjustment to this link was required for a variant product change, it is likely that the cam follower and pushrod need modification as well. Keeping the existing lengths for the cam follower and the link elements, a dimension of 400mm is selected for the pushrod as this lies in the middle of the range, and decreases the potential for sensitivity problem near the boundary of expectable dimensions.

8.1.9 STEP 8: Potential redesign stage

The construction of the pushrod is a hexagonal bar with threaded ends for coupling. The simplest solution to change the length is the inclusion of a coupler nut (cf. figure 8.9) this could be threaded internally the opposing left and right hand threads, the corresponding threads should be added to the pushrod and pivot coupler. With the addition of two locking nuts, the new length for the pushrod can be adjusted and fixed. This simple design solution gives a configuration to process the new sweet, and adds new processing flexibility to the mechanism for future new products.

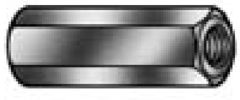


Figure 8.9 Coupling nut

One limitation that has become evident in the representation of the envelopes using the convex hulls is: the hull plots the minimal convex shape containing the given data, and it can envelop a void in the points where the equipment does not function successfully. For this reason the convex hull must be regarded as only an approximation of the region of acceptable working. In previous case studies this has not been a problem, as the analysis and optimization is performed on the raw data produced in the functional matrix.

8.2 CASE STUDY 2: Over-wrapping

The following problem is the investigation into the capability of an existing packaging system to handle dual product changes: new lighter packaging medium and a geometrically different box with cost implications.

8.2.1 Equipment

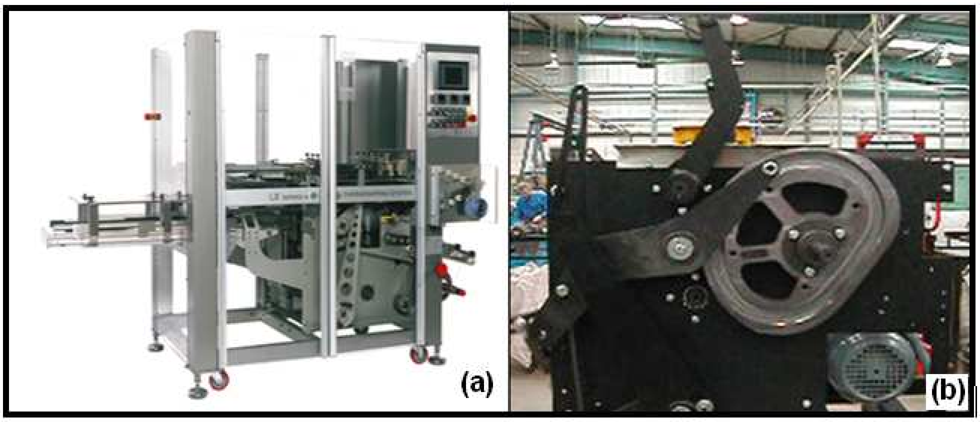


Figure 8.10 The equipment

Over-wrapping machines, an example of which is shown in figure 8.10a, are used to wrap film around products such as food cartons or consumer goods.

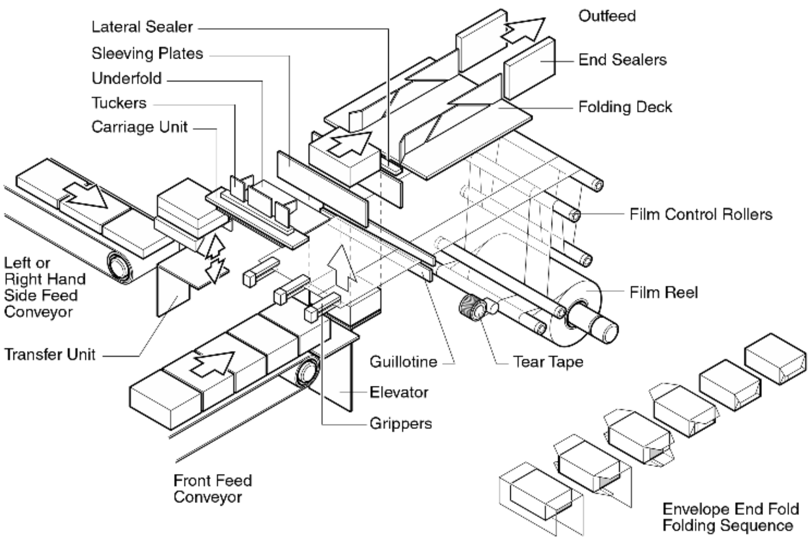


Figure 8.11 Over-wrapping sequence (courtesy of Marden Edwards)

The general operational sequence for the over-wrapping machine is as follows: The pack is fed from the line into the machine via conveyor. Pack is raised via the elevator mechanism through the sheet of tensioned film which is cut to length, raised taking the cut film with it through the sleeving plates which effectively drape the sheet of film tightly over the pack. The forward motion of the under-fold fingers attached to the advancing carriage unit then folds the trailing edge of film at the back of the pack under. As the carriage continues to advance, the tucker plates form the tucked edges at the back of the pack before the pack is pushed off the fingers and transferred onto the folding deck. As the pack moves onto the folding deck, the leading edge is folded under at the comb-bar such that it overlaps the trailing edge under-fold and the leading edge tucks are created by the front section of the folding plates. The pack is pushed just the right distance to leave it over the lateral sealer bar which is raised to perform the base seal at the overlap point. Subsequent packs transferring onto the folding deck push the preceding packs through the folding plates to fold first the bottom overhang, then the top. Finally the end sealers seal the end faces of the pack before out feed. Motion of the product and machine is produced by a series of cam driven spatial mechanisms. These are actuated by a central transmission box (cf. Figure 8.10b).

8.2.2 STEP 1: Processing constraints identification

The machine is required to process a lower value product; this dictates that the machine must now process the new product more quickly to maintain the same level of productivity. An increase from 60 parts per minute to 120 parts per minute is needed. With thinner films, generally slower process speed is required. As the increased motion speed of the product rising through the film can either damage (i.e. tear or stretch) product or affect the cut length, giving inadequate material to complete full overlap. To accept the new product, the input conveyor could be lower, as the main pack heads on the top of the machine are fixed. This then requires the elevator to start at a lower position and make up the new displacement. As identified earlier, further constraints are presented for processing the new product. Because the up stoke of product through the packaging medium also de-reels the medium, tests show a safe acceleration of 2g which the producer has specified. Engineers also have fixed a 2.5g working limit on the acceleration of the moving parts of the system.

8.2.3 STEP 2: Establish, validate and verify model

A parametric model of the full transmission system was constructed within the constraint modelling environment. Figure 8.12 shows wire frame models of the mechanism produced within the modeller (both front and isometric views). Effectively the system configuration is five cam driven sub-mechanisms, which actuate all the packing functions. Constraint optimization is employed to maintain connectivity and relations as the system is activated.

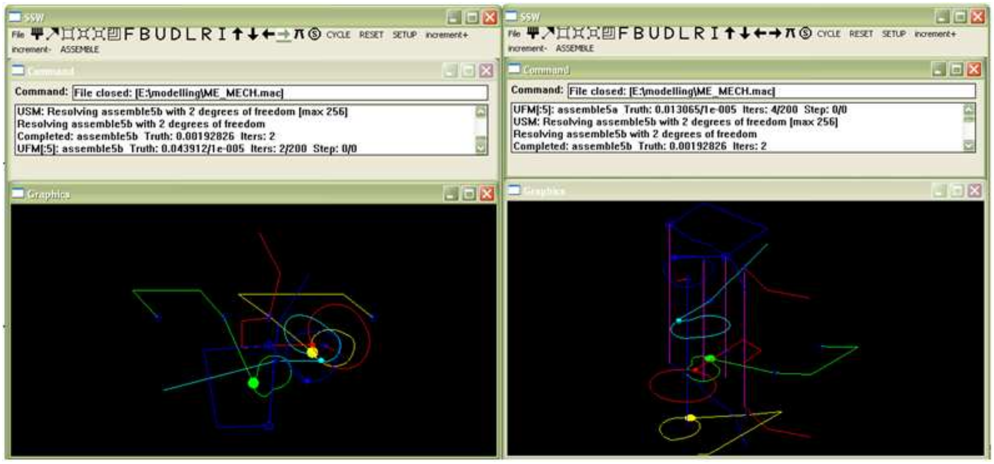


Figure 8.12 constraint model of transmission mechanism

8.2.4 STEP 3: Definition of failure mode constraints

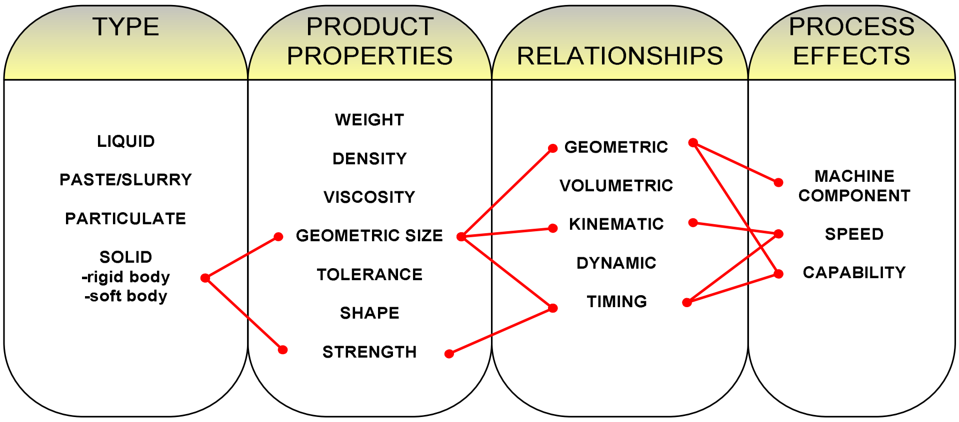


Figure 8.13 Relationship diagram

At this stage the effects of product and process must be considered. There are two product changes, geometric and film strength. This implies that the modelling and investigation must take into account geometry, kinematic and timing constraints. With the visualization of the final analysis, machine component changes, speed and process capability must be represented. These are reflected in the relationship diagram figure 8.12.

Table 8.2 Transmission mechanism failure mode constraints

	Failure mode constraints	Description	Association
a	Geometric	20mm taller	Product
b	Kinematics	2g limit of packing medium acceleration	Product
c	Kinematics	2.5g limit on mechanism acceleration	Machine
d	Timing	10° Cam Start position	Machine
e	Timing	150° Cam finish position	Machine
f	Mechanism deconstruction	Breakage in mechanism	Machine
g	Geometric	Element motion lie out side machine footprint	Machine
h	Collision	Interaction of elements through cycle of machine	Machine

8.2.5 STEP 4: Associate failure mode detection to models

Failure mode detection is added to the model in the same way identified in the previous case study. Constraint monitoring is then used to check for violations of the constraints identified

8.2.6 STEP 5: Disturb model for inherent adjustment

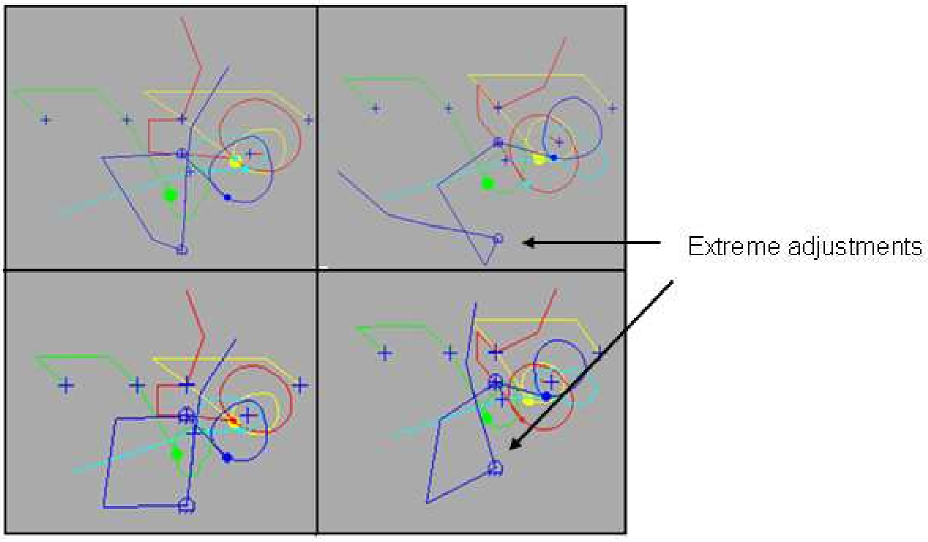


Figure 8.14 Inherent adjustment modelling

Analysis was performed on the transmission mechanism, utilizing the inherent adjustments of the individual elements of each mechanism, shown in figure 8.14. Constraint monitoring was employed to check for any violations of the defined constraints. Results of this investigation have shown that although relative start and finish displacements could be altered, no effective solution was possible for the new product and its respective constraints, further to this, it was shown that four of the sub-mechanisms do not compromise any design laws e.g. cam transmission or pressure angles, and the kinematics values, when the operation speed is increased and additional displacements are applied for the new product. The limiting part of this system is the elevator mechanism. The mechanism is required to push the product through the packaging medium and into the wrapping station. The elevator of the machine is required to return quickly to the start position, so as not to interact with other parts of the machine.

8.2.7 STEP 6: Disturb for potential configuration

Figure 8.15 shows a wire frame model of the elevator mechanism produced in the constraint modeller. Item 1 is the drive cam, 2 the cam follower, 3 cam follower pivot, 4 connection rod, 5 is the elevator block (constrained to move up and down) and 6 is the cam follower arm.

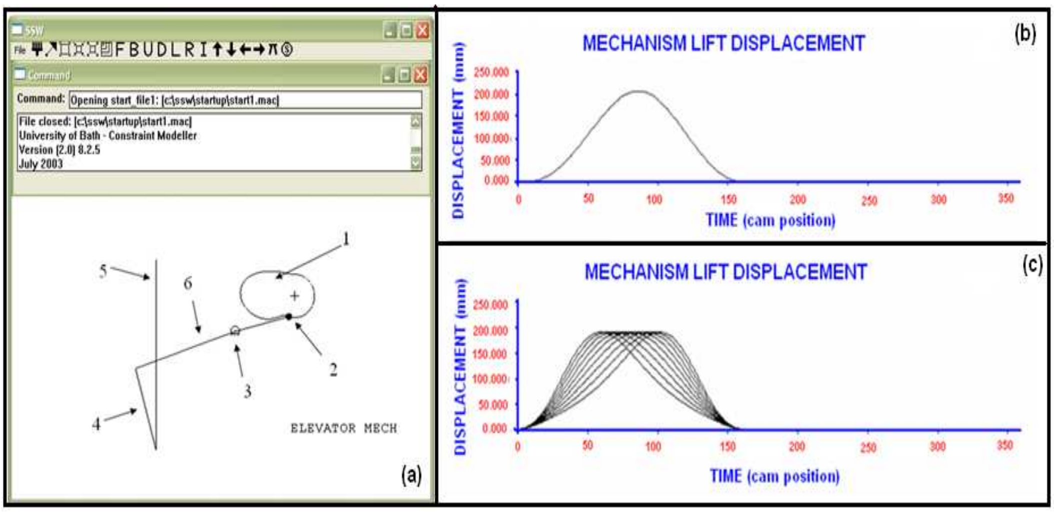


Figure 8.15 Constraint model and displacements

Further constraints for the models function are the attachment of the cam follower on the pivot. The cam follower must remain in contact with the drive cam throughout motion and the connection rod maintains connectivity between cam follower and elevator block. The *model space* hierarchy for this model can be found in appendix C.

Figure 8.15b shows the displacement profile for elevator mechanism. Before considering any modification to this profile, the functional constraints have to be considered (cf. table 8.2). The displacement distance is fixed as it is required to transfer the product from the base of the machine to the packing height. The start and stop points are also critical as they are timed with other sub mechanisms within the machine; the product is required to be in place by the time the cam has reached 150°. This leaves the position of the peak of the lift profile as the only factor that can be modified. The timing for the lift relates to the rotational movement of the cam. The lift profile can be described by a sinusoid. To adjust the peak position, the sinusoidal motion law was modified. This modification was calculated to give peak positions from 10° to 150° cam timing. Some of the modifications can be seen in Figure 8.15c.

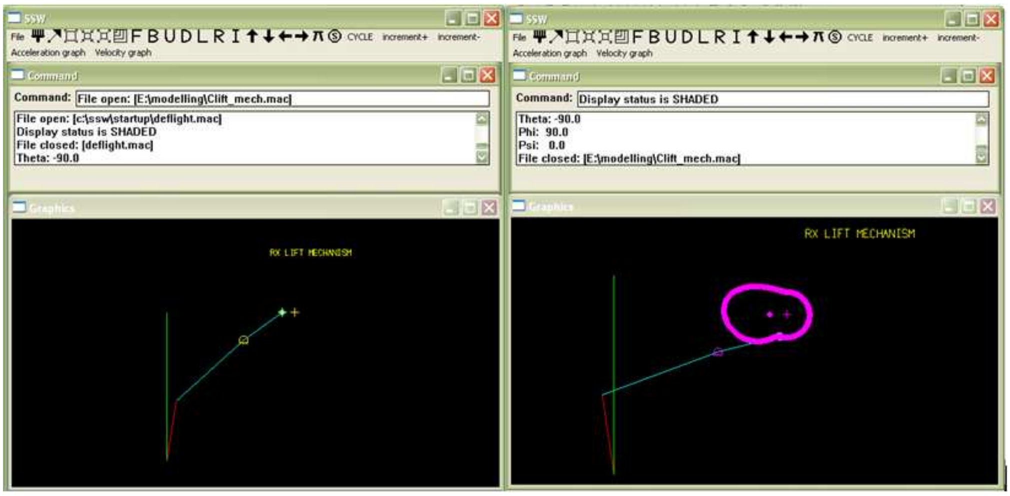


Figure 8.16 Reverse engineering of the cams

The points from the modified sinusoid are employed as the drive geometries for the end effecter of the elevator. As the elevator is moved, the *model space* where the cam would be positioned is rotated. With each movement of the elevator, a point is transferred from the end of the cam follower into the cam *model space*, effectively, reverse engineering the cam profile. This process can be seen in figure 8.16. Cams profiles in the modeller can be constructed using the closed B-spline form. These were obtained so that the curve passed through the required points. Each cam profile was saved sequentially in a text files. Some of the multiple instances of the cams can be seen in plotted in figure 8.17. These files were read back into the modeller and then run as the drive cam.

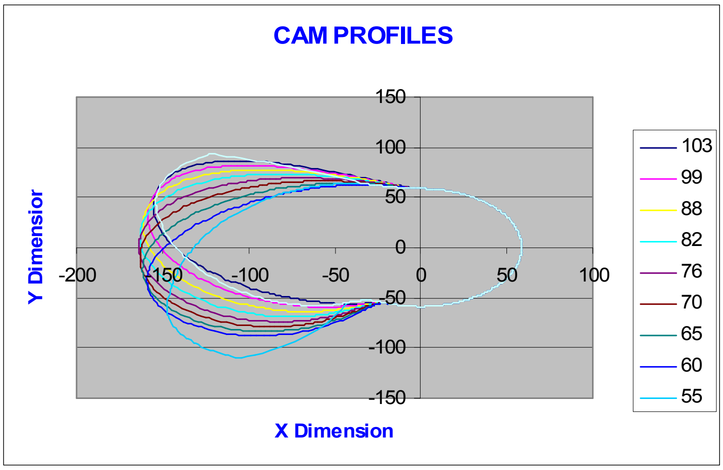


Figure 8.17 Examples of cam profiles

8.2.8 STEP 7: Evaluate and represent results

The acceleration and velocities were then logged against each profile and compared, as shown in figure 8.18.

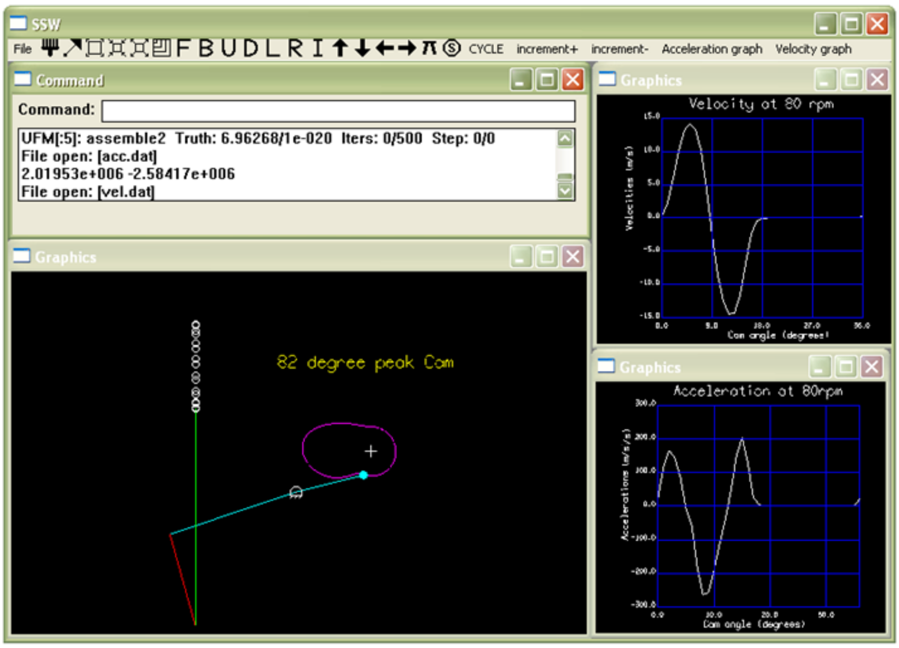


Figure 8.18 Constraint-based analyses of cam driven motions

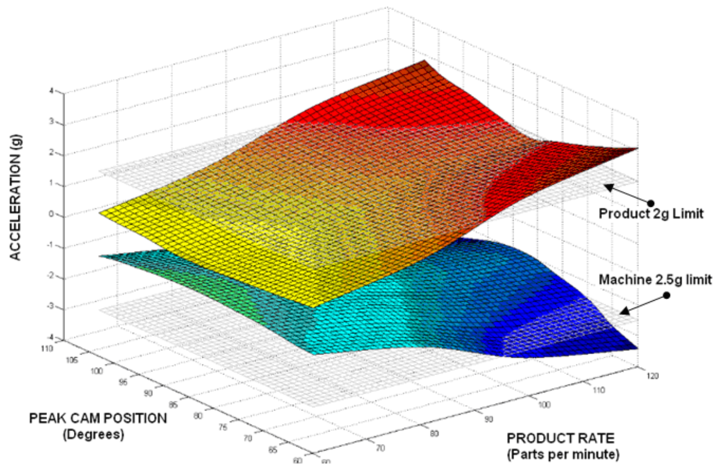


Figure 8.19 Surface representation of results

For visual representation, surface plots (figure 8.19) have been constructed from the results of peak accelerations plotted against production speed (parts per minute). The acceleration is plotted for both up and down strokes of the elevator. Both acceleration limits are identified on the plot.

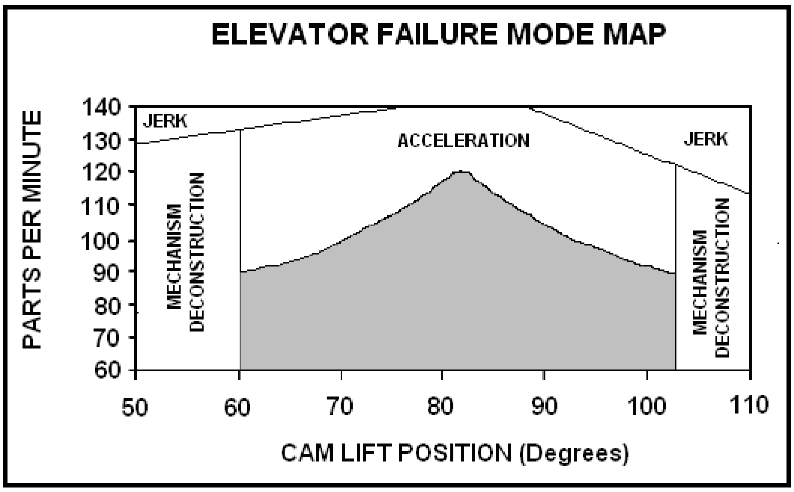


Figure 8.20 Failure mode map

The surface plot offers a complex visualization that can be difficult to interpret. For this reason the results are used to plot the failure mode map (figure 8.20). The acceleration and mechanism deconstruction failure modes are the dominant factors in failure of the mechanism, so only these are considered. By inspecting the FMM is it evident that the goal of doubling the production speed to 130 parts per minute is impossible as the acceleration failure mode is invoked. What can be seen is that if a peak profile of 82° was used, it would be possible to increase the production to 118 parts per minute, although this would mean running the process at its limit.

This solution still is 9% lower that was required, so after further discussions with the producer, an attempt was made to utilize the existing cam profile for the elevator mechanism, and, to add additional flexibility to the system for future products.

8.2.9 STEP 8: Potential redesign stage

Further investigations were performed using a new configuration: employing a 'piggy-backed' linear drive mechanism on the top of the elevator block. This has the effect of changing the overall displacement of the top point of the elevator block and also changing the acceleration profiles. A wire frame model of this addition mechanism can be seen represented in figure 8.21. As with the previous model, constraint optimization is employed to maintain connectivity of model.

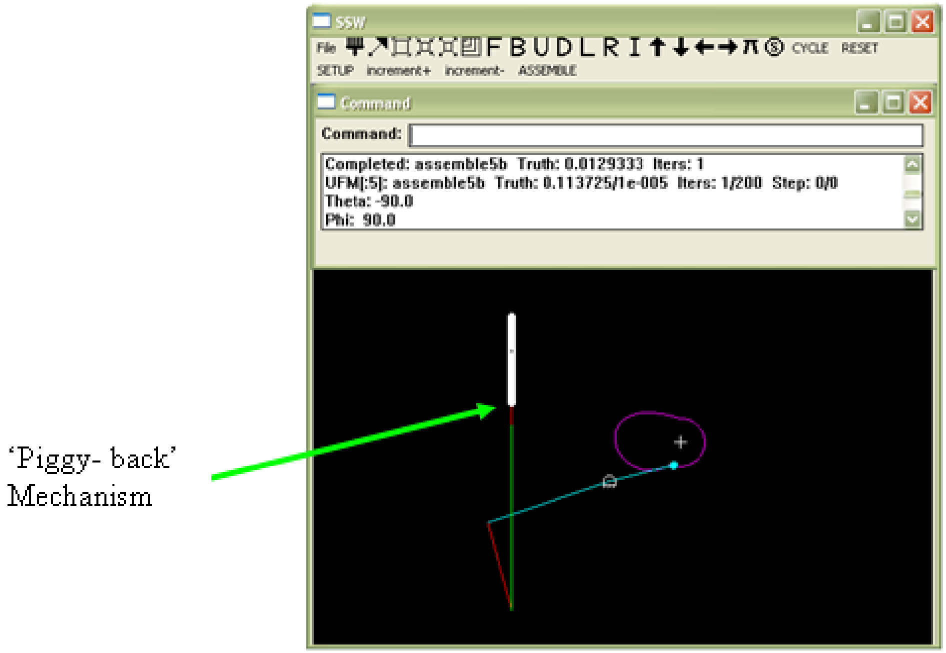


Figure 8.21 Elevator add-on mechanism

Results from this investigation highlighted that for the single product change example, the effects on dynamics outweighed any gains over cam alteration and potential flexibility for the case study. But if further multiple variant products were required, this modification has some merit. With this case study, the approach of this thesis has been employed to investigate the capability of an existing packaging system to handle dual product changes: new lighter packaging medium and a geometrically different box with cost implications. In conclusion, the approach proved to the producer that the current design is at the limit of its capability, and a new solution has to be sought.

8.3 CASE STUDY 3: Pick-and-place unit

The following problem is the investigation into capability of a pick-and-place robot to process a different product into a different pack configuration and to find the optimal packing setup in consideration of time.

8.3.1 Equipment

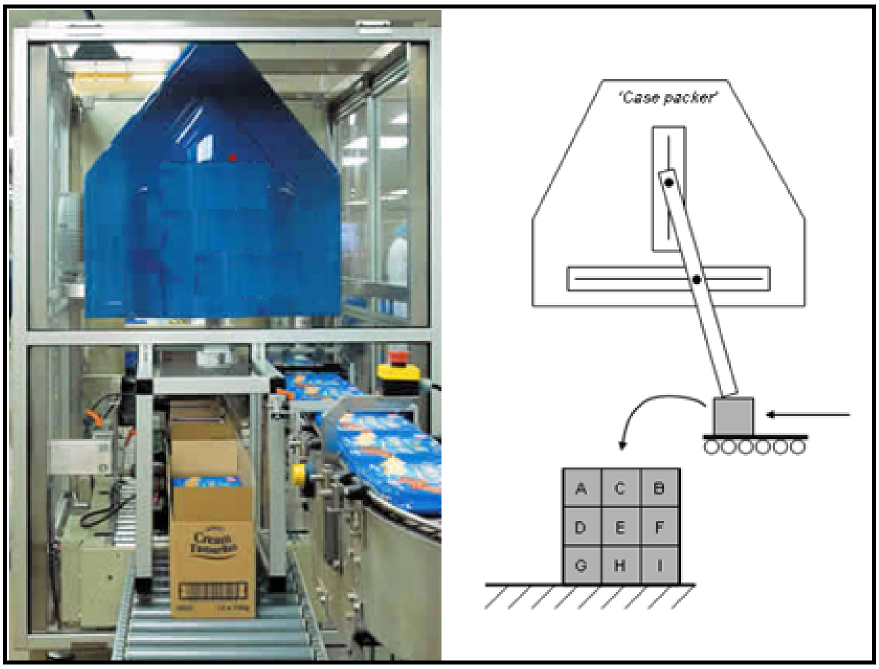


Figure 8.22 Casepacker

The *Casepacker* is a pick-and-place robot. It is unique in its construction, as actuation of the pick-and-place arm is given via two linear drives. It is used typically for secondary packaging operations. This is where primary packed products are placed in a corrugated cardboard case to be sent to the producer. It should be mentioned that this pick-and-place procedure is only a two dimensional problem. Thus all the geometrical coordinates consists of two values only: the x component for the horizontal axis and the y component for the vertical axis. The primary packed products arrive at the *Casepacker* on a conveyor, which can be seen on the right hand side of figure 8.22.

8.3.2 STEP 1: Processing constraints identification

The producer has the case packer utilized on a packaging line. The product is being changed from a rigid bodied bottle (single pack configuration); to a semi rigid pack of frozen cauliflower with a weight of 1kg (multiple pack configurations). The end effector vacuum cup needs to be changed to suit this product, so the producer needs to know:

- Is the case packer capable for the new pack configuration?
- Does it have the reach in combined x and y directions?
- Does the product motion, further constrain the problem?
- If the process proves capable before or after any required modifications, what is the best possible solution to pack the product? *i.e.* the optimal motion path for the end effectors (process time reduction).

The producer wants to keep the existing positions of the case packer: output box conveyor and product conveyor, so existing product can still be packed. This potentially entails increasing the performance envelope (cf. chapter 6).

8.3.2.1 The product

In previous case studies the product related constraints were either obvious for example the size of the new sweet bar (case study 1), or are supplied by the producer (the motion constraints for product moving through film). With the *Casepacker* initially there were concerns that there could be a ‘peeling’ effect with the vacuum cups in two places: as the product is picked and accelerated, then it is decelerated and placed. To understand this, a small investigation was required to obtain the motion against weight constraints for the product. Full details of this can be found in appendix D part D1. The results from this gave us a maximum acceleration range of 8.01m/s^2- 10.71m/s$^{2.}$ This constraint has to be included the model.

8.3.3 STEP 2: Establish, validate and verify model

A constraint-based model of the *Casepacker* (Figure 8.23) is constructed with the constraint modeller. The *model space* hierarchy for this model can be seen on appendix C.

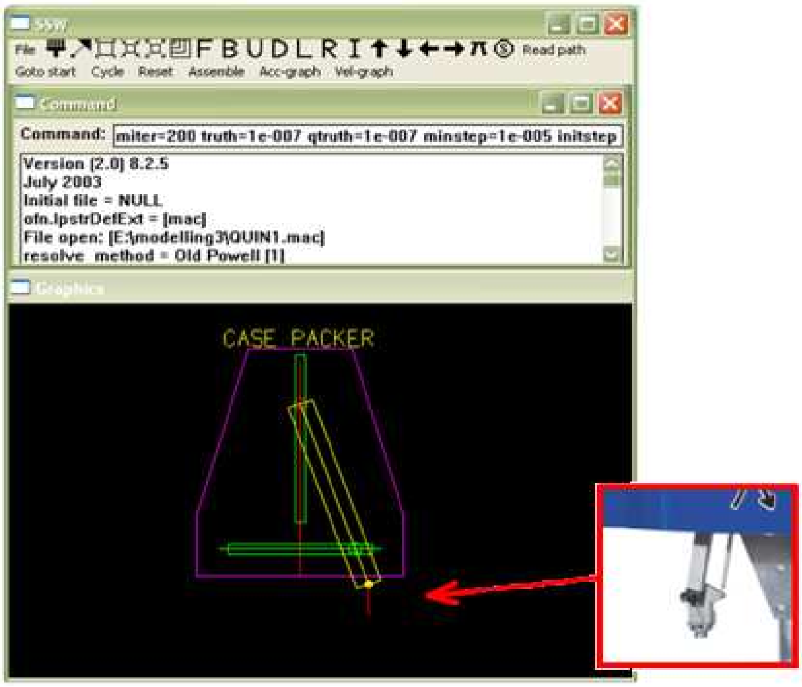


Figure 8.23 Constraint model of Casepacker

As with previous models, constraint optimization is employed to maintain connectivity between elements, it is also used to ensure the end effector follows the curve. Points are embedded in the *model spaces* that represent the slideways. These *model spaces* are bounded (as noted in chapter 7) to the maximum displacements of the respective slideways. The top of the pick-and-place arm is constrained to the y slide point, and the arm is also constrained to lie on the x pivot point. Motion is induced by the end effect being constrained to follow a curve given as a series of points read in from a text file. The inset of figure 8.25, shows the end effector used on the existing product. This will be adapted for this case study, as it always keeps the product parallel to the pack conveyor. The end effector has a limit of +/- 60° from vertical before the product moves away from parallel, so these constraints are added to the model.

8.3.4 STEP 3: Definition of failure mode constraints

It is a soft bodied solid product, for this packaging problem it gives three distinct properties, geometric size, shape and strength. These imply that any modelling requires the following relationships to be handled: geometric, volumetric, kinematic, dynamic and timing (cf. Figure 8.24). For evaluation purposed any visualization needs to represent machine component, speed and capability properties. Further investigation of the factors presented in figure 8.24 gives the series of constraints which must be monitored for violation throughout the modelling process (table 8.4).

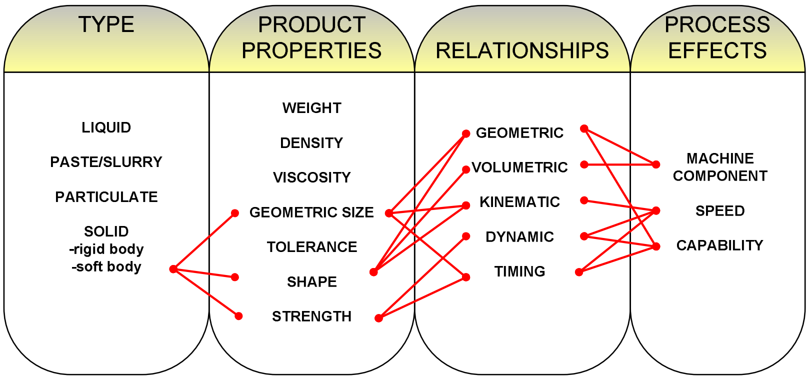


Figure 8.24 Relationship diagram

Table 8.3 Case packer failure mode constraints

	Failure mode Constraints	Description	Association
1	Kinematic	X drive acceleration	Machine
2	Kinematic	Y drive acceleration	Machine
3	Mechanism deconstruction	Breakage in configuration	Machine
4	Displacement	Insufficient allowable motion of arm	Machine

5	Displacement	Excessive required motion of end effector	Machine
6	Kinematic	Product deceleration	Product
7	Kinematic	Product acceleration	Product
8	Collision	Product interacts with box	Machine to product
9	Collision	Product contacts conveyor	Machine to product
10	Collision	Product interacts with machine frame	Machine to product
11	Collision	Product interacts with other packed product	Product to product

The product is to be packed into a 300mm square box. The products, which have the dimension of 300mm x 100mm, can be positioned on nine different locations (A-I) in the box (figure 8.25) three layers with three items each. The different layers will be filled from the right to the left (cf. figure 8.24). Consequently the first product which will be placed is product I, before H and G are introduced. In figure 8.24 the geometrical locations of the nine spots are given. The products are not cuboid, due to their content, this allows for some leeway in the packaging positions.

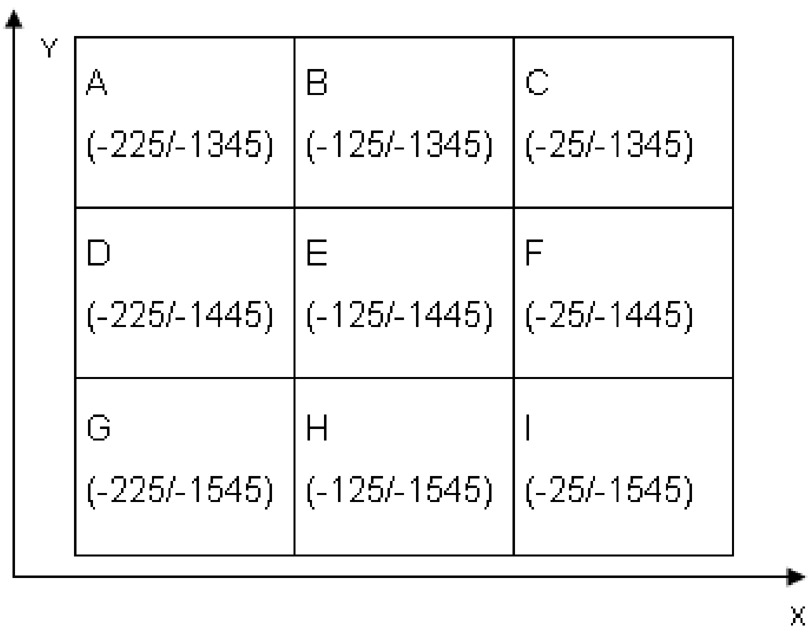


Figure 8.25 Geometrical locations of the nine drop points

8.3.5 STEP 4: Associate failure mode constraint detection to models

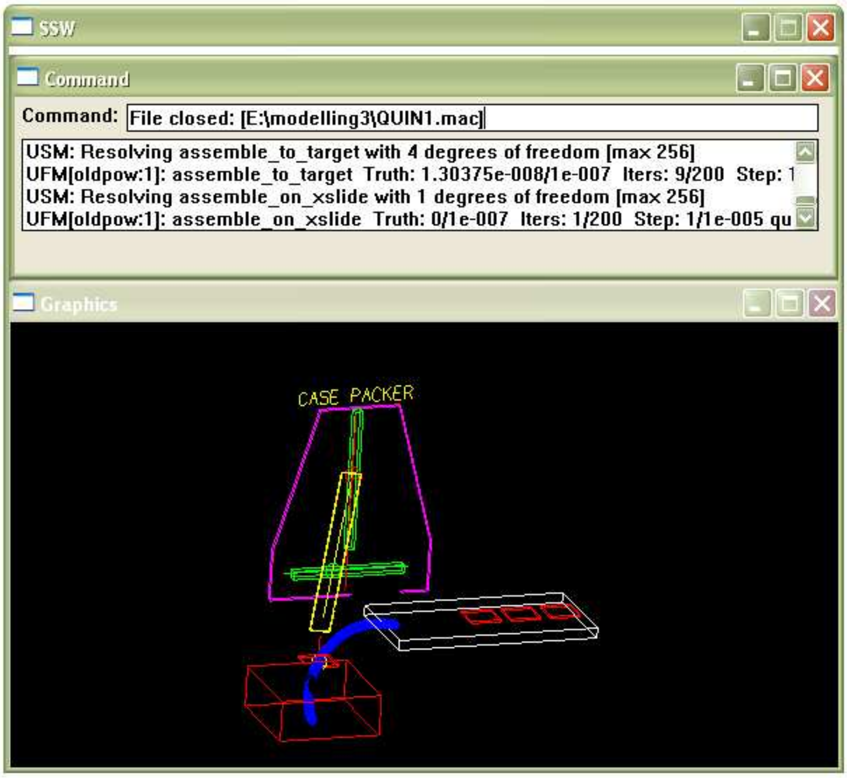


Figure 8.26 Constraint-based model of packaging scenario

Failure mode detection is added to the model in the same way identified in the previous case studies. Specifically, solids are added to represent the product, machine frame, conveyor and packing box (cf. figure 8.35). These for failure modes 8-11 (table 8.4). As identified in chapter 7 table 7.3, truth maintenance is used for mechanism deconstruction, failure mode 3. And, motion mapped placement in Cartesian space used for displacement (4 and 5) and kinematics (1, 2, 6 and 7). Constraint monitoring is then used to check for violations of the constraints identified in table 8.4.

8.3.6 STEP 5: Disturb model for inherent adjustment

For this case study the requirement of this the step is, to establish the limits of the machines function reach (envelope of performance).

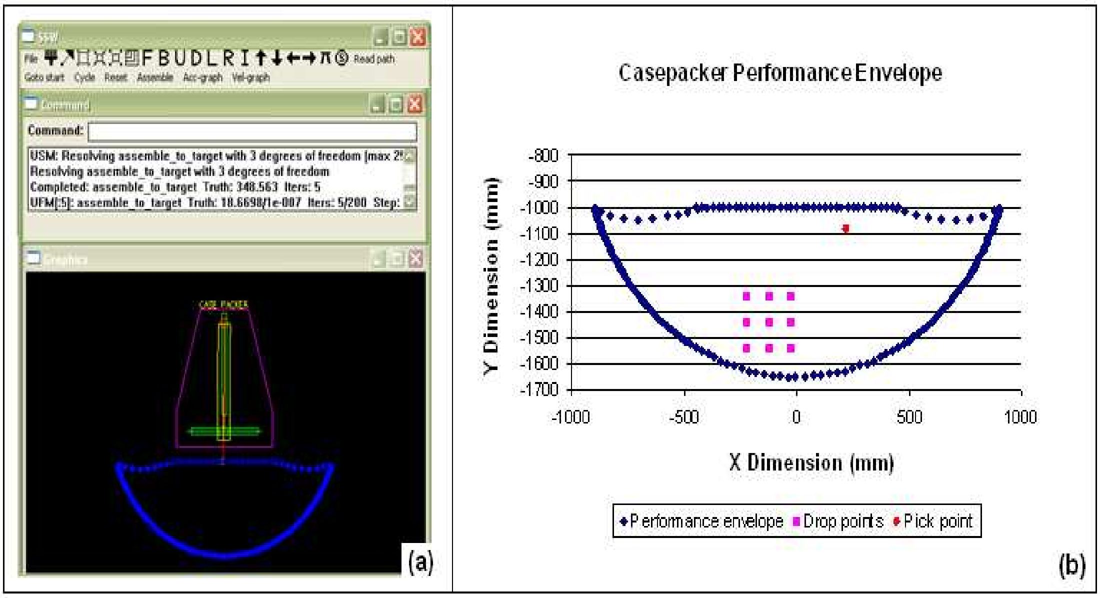


Figure 8.27 Performance envelope production

The approach is produced a circle of points, with a radius double that of hypothetically reach of the arm. The centre of the radius is the centre of the machine. The points of the circle are used as the goal positions for the end effector. Tiered constraints (cf. Figure 4.2) are used in the production of the envelope. Constraints were employed to ensure connectivity and function of the core mechanism; these being the hard constraints noted in chapter 4. Constraints optimization is then employed for the goal of the end effector reaching the points of the circle. This goal is a 'soft' constraint, as identified in chapter 4. Constraint monitoring was then employed to check if any of the constraints are violated. As described in chapter 6, the successful points are recorded and used to produce the performance envelope Figure 8.26. In this instance the performance envelop directly relates to configuration spaces noted in chapter 2 (Agrawal, 2001; Meret, 1995). The result of this process shows that the existing setup has the capability to manoeuvre the product between the pickup point and each of the nine drop points. These are shown respectively on figure 8.27b. The fact that the *Casepacker* proves capable of the required motion negates the need to investigate for the envelope of opportunity, so step 6 of the approach is not required.

8.3.7 STEP 7: Evaluate and represent results

In finding the optimal curve for the motion of the product, we are constrained by the pick-and-place positions. The investigation strategy is to create a number of representative Bézier curves by diversifying the control points (x_1, y_1) and (x_2, y_2). A further constraint for the total motion time is added (in this case 1 second), by comparing the maximal acceleration a_{max} for the cycle time of one second of the different curves (same start and end points but variable control points) the optimal motion path with the lowest acceleration can be found.

Table 8.4 Analysis of curves

PLACING POSITION	CONTROL POINTS	a_{max} [m/s²] for t =1sec	CONSTRAINT VIOLATIONS
A	$(x_1,y_1) = (94,-940)$ $(x_2,y_2) = (-265,-1020)$	2.083	Geometrical constraints: product B and wall of box on the left hand side; ideal curve causes collision; heavily modified, steeper version has to be used
B	$(x_1,y_1) = (90,-1000)$ $(x_2,y_2) = (-165,-1100)$	1.597	Geometrical constraint: product C; ideal curve causes collision; modified version has to be used
C	$(x_1,y_1) = (100,-1000)$ $(x_2,y_2) = (-90,-1150)$	1.254	No additional constraints; ideal curve can be used
D	$(x_1,y_1) = (30,-1000)$ $(x_2,y_2) = (-250,-1150)$	1.656	Geometrical constraints: product H and wall of box on the left hand side; ideal curve causes collision; modified steeper version has to be used
E	$(x_1,y_1) = (20,-1000)$ $(x_2,y_2) = (-160,-1200)$	1.662	Geometrical constraint: product F; but ideal curve can still be used
F	$(x_1,y_1) = (40,-1000)$ $(x_2,y_2) = (-150,-1250)$	1.637	No additional constraints; ideal curve can be used
G	$(x_1,y_1) = (-50,-1000)$ $(x_2,y_2) = (-250,-1300)$	1.847	Geometrical constraints: product H and wall of box on the left hand side; but ideal curve can still be used
H	$(x_1,y_1) = (-25,-1000)$ $(x_2,y_2)=(-225,-1300)$	1.935	Geometrical constraint: product I; but ideal curve can still be used
I	$(x_1,y_1) = (-25,-1000)$ $(x_2,y_2)=(-210,-1350)$	2.078	No additional constraints; ideal curve can be used

The complete process for this can be seen in Appendix D, parts D2 and D3. The optimal curve identified, is then applied to the constraint model shown in figure 8.25. Additional solids are added inside the packaging box to replicate the existence of pre-packed products.

Taking into account the constraint violations identified in table 8.5, some of the curves had to be modified. Again this took the form of modifying the control points of a range of Bézier curves as identified in Appendix D. The resultant modified curves were then run in the model; constraint monitoring was again employed to check if constraints had been violated. The resultant functioning curves can be seen plotted in figure 8.28.

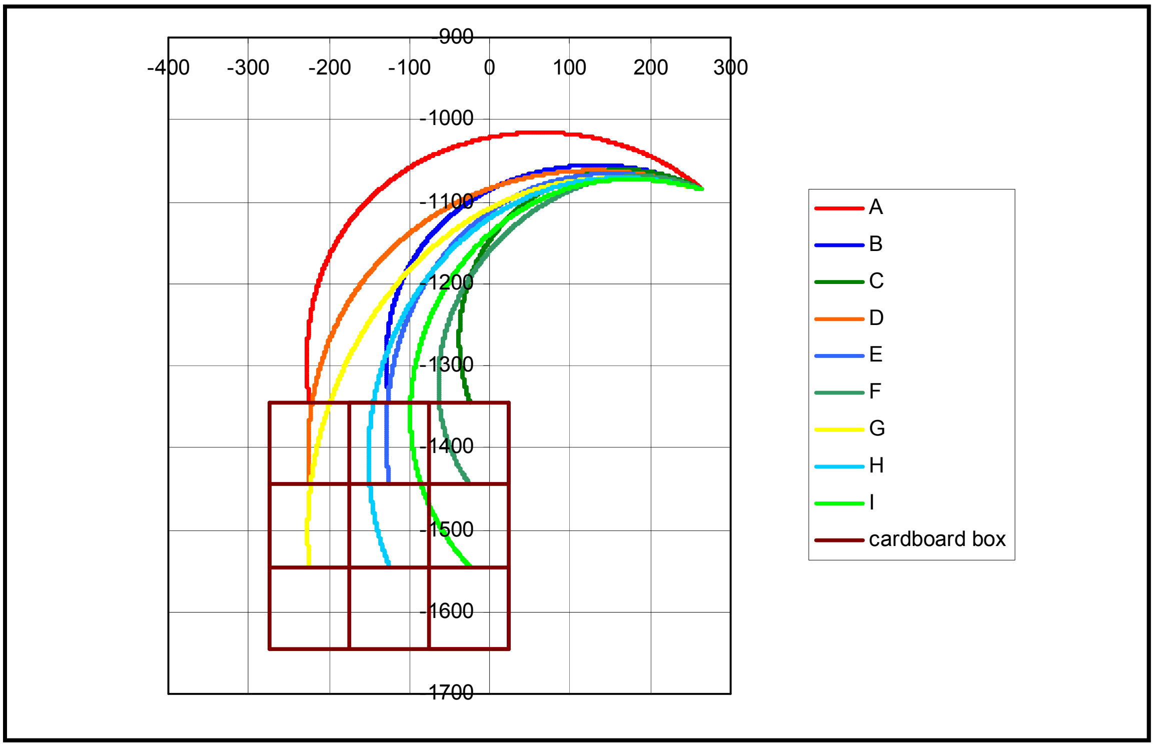


Figure 8.28 Ideal curve selection

8.3.9 STEP 8: Potential redesign stage

As an example of how to use the presented results, in the following the calculation of the minimum cycle time for one product specification is carried out. Assuming that the product is a package of JC film (cf. appendix D) with a flat surface and a weight of 2.5 lb (almost equates to the 1kg product load), the maximal allowable acceleration is the smaller the accelerations (8.01m,s^2) found during the experiments for this product specification and thus $a_{max,\ exp}$ = 8.01m/s^2. In table 8.5 the results of the calculation can be seen.

Table 8.5 Optimal results for pick and place

POSITION	a_{max} [m,s^2]	$a_{max,,exp}$ [m,s^2]	t_{min} [sec]
A	2.08	8.01	0.520
B	1.60	8.01	0.399
C	1.25	8.01	0.313
D	1.66	8.01	0.413
E	1.66	8.01	0.415
F	1.64	8.01	0.409
G	1.85	8.01	0.461
H	1.94	8.01	0.483
I	2.08	8.01	0.519

With this case study the approach has been employed to investigate the inherent capability to process a variant pack configuration and new product. The approach shows how the existing equipment had the capability to process the product via the use of the performance envelope production in the constraint modeller. The approach was continued to find the optimal processing time for the product. The results of this process were then analyzed in the modeller to validate if the optimal results could be used, and modifications applied where the optimal results violate the identified constraints from table 8.4.

8.4 CHAPTER CONCLUSIONS

This chapter has shown the successful use of the constraint-based approach presented in chapter 7, for assessing the capabilities of machine systems. It has also shows the importance of identifying the constraints of both product and machine for assessment and redesign activities. The three case studies were picked to show that each new product application to exiting machines places different demands on the approach presented in chapter 7.

Case study 1 shows how the approach was used to assess the limit of the existing ejection mechanism, then by employing limits modelling to find the envelope of opportunity, and a solution configuration for the new sweet. The change of configuration was presented as the solution for the producer, and a coupling nut given as one option. It should be emphasised that, although the solution given was simple, it was the approach that presents this outcome without the need for trial and error tests by the producer.

In case study 2 the approach applied to an existing over-wrapping machine configuration. The approach assessed the existing configuration and by investigating its performance envelope, it was shown that the configuration could not satisfy the producer's needs. Variational modification was applied to the cam of the elevator mechanism using the constraints within the modeller. The results of the process were presented using a failure mode map. This map presents the functional area and the constraints which would be violated if certain variation configurations were applied. The results of this concluded that the solutions based around the cam could not satisfy the producer's needs. Further configurations were tried using a secondary mechanism but these also failed the producer needs. The approach shows that machine lay at the limit of its design.

In Case study 3, the approach was required to assess the existing process configuration. By producing its performance envelope based on the extreme motions of the machine, it was shown that the system was capable to pick-and-place the new product. Optimal curves were identified for the motion of the system. These were employed as motion drivers. The modeller checked for constraint violation and presents optimal curves.

In summary the three case studies also have shown how:

- the approach can be employed to find the inherent capability of a system (performance envelope)
- the approach can be employed to find the potential capability of a system (opportunity envelope)
- constraint processing techniques: monitoring, satisfaction and optimization are employed throughout the process of modelling, assessing and redesign for equipment processing new or variant products.

This chapter presents research that fulfils key objective 6 from chapter 1. The next chapter concludes and defines the contribution of the research presented in this thesis.

Chapter 9

Conclusions and future work

"The strongest arguments prove nothing so long as the conclusions are not verified by experience"
Roger Bacon

In this research a constraint-based approach to assess the capability of existing equipment to handle product variation has been presented. In this chapter the conclusions of the research will be discussed. This is performed by relating the achieved results to the objectives formulated in chapter 1, and in context of the three hypotheses defended in this thesis:

- *It has been shown that generic process can be formed to identify the limiting factors (constraints) of variant products to be processed.*
- *Also that, the identified limiting factors (constraints) can be mapped to form the potential limits of performance for a system.*
- *And, that limits of performance of a system (performance envelopes), can be employed to assess the design capability to cope with product variation.*

This chapter gives concluding remarks about the research presented, and ends with some directions for future research.

9.1 THE OBJECTIVES OF THIS RESEARCH REVISITED

It was presented in chapter 1, that, in order to investigate the three hypotheses, a number of key objectives for the research had been addressed:

- To demonstrate the effectiveness of product and process constraints in the design and manufacturing domains.
- Investigate and critically appraise contemporary research in the area of the problem presented in this thesis.
- To investigate the relationships of the product and processing constraints.
- To investigate an approach where, the performance envelopes of an existing machine can be established.
- To investigate an approach where, with the performance envelope established, it can be used to assess the machines ability to process variant products.
- To validate the approach through its application on industrial case studies.

An additional sixth objective was the critical investigation of related research. The following discusses how these objectives had been dealt with.

9.1.1 Usefulness of constraints in design and manufacturing

This objective was addressed in chapter 3; it was shown that constraints and their respective approaches aid both design and manufacturing activities. Also it was shown that for any approach employing constraints for design and manufacturing activities, a grouping of constraints had to be considered. These are:

- *Constraints in design:* Geometric, functional requirements, relationships between functions, connectivity between elements, and system topology.
- *Constraints in manufacturing:* Motion limits, required motion, position, kinematics, component damage, component interaction and precedence.

In chapter 4 of it has been shown there is a set of generic constraints for a product to be processed (cf. figure 9.1a). Additional, as the emphasis of this research, has been targeted at the functionality and performance. When simulating and modelling processing, it has been shown in chapter 5, that there is a group of seven generic constraints that have to be handled within any modelling approach for machine and mechanisms that are employed for the processing of products. These are shown in figure 9.1b

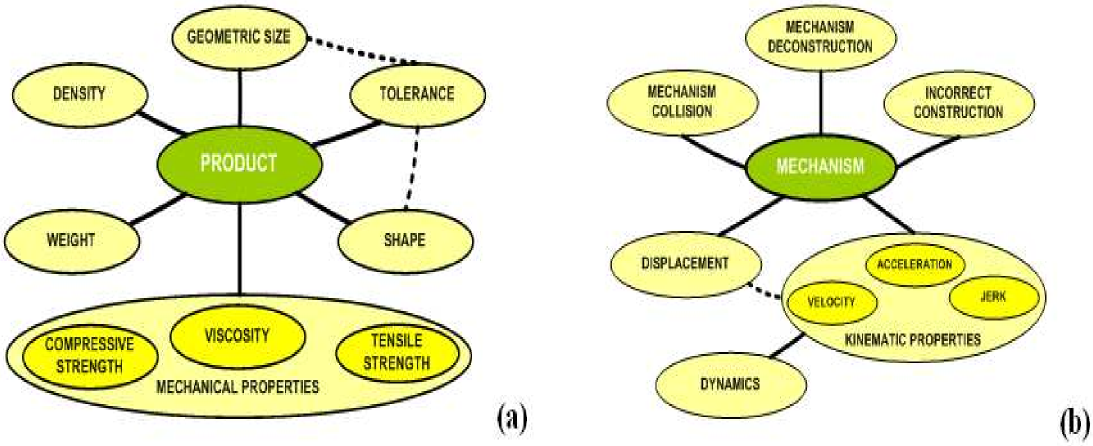


Figure 9.1 Product and process constraints
(adapted from figures 4. and 5. respectively).

9.1.2 Critical analysis of contemporary research

In chapter 2 the state-of-the-art for four subject areas which relate to the search for a solution to the problem stated. These areas have been: engineering design, modelling and simulation, workspace and performance analysis and multi-variable representation techniques. The outcomes from this chapter were that currently there is no approach to answer the specific industrial question posed in this thesis.

9.1.3 Relationships of product and process constraints

This objective was addressed in chapter 6. This shows that the relationships of product and process, and their influences, allow the engineer to understand and visualize the processing capabilities. Each variant to be processed has a different set of constraints; these present different problems to the machine and therefore to any respective models. An example of this is a transfer mechanism for a frozen pudding line (figure 9.2), three product properties (column 2) need to be measured: geometric size, shape and strength, these invoke certain constraint relationships, and in turn, these impose specific effects on the system.

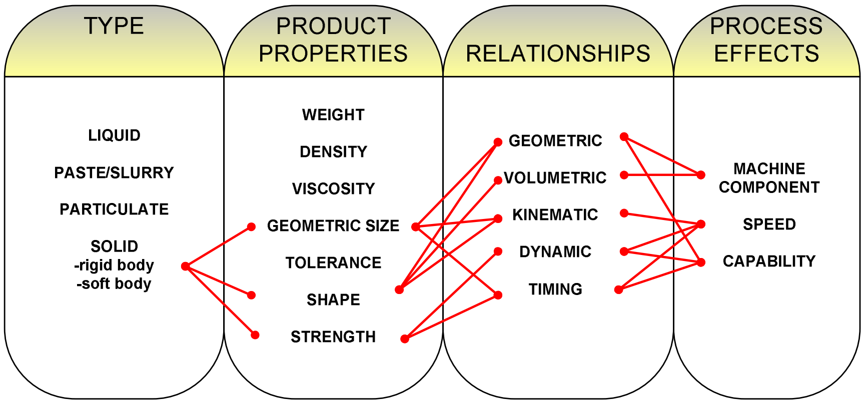


Figure 9.2 Relationships for a frozen pudding transfer

The constraint relationships (figure 9.2 column 3) are the factors which any model must cope with, and the process effects (column 4) are the factors which any visualization technique must present for evaluations. It was shown in chapter 6 how these factors change as the product changes. This was further highlighted in the case study examples in chapter 8.

9.1.4 Establishment of performance envelopes

This was also addressed in chapter 6. It has been shown that two levels of envelopes need to be considered while investigating machine capability: the *envelope of performance* (cf. Figure 9.3a) is the area where the machine will function, using only the inherent design adjustments. This thesis also introduces a new definition, the *envelope of opportunity* (Matthews *et al,* 2006d). This is the area where the design will function after external modification to configuration. The approach presented here not only allows the user to analyse the inherent flexibility of the system, but also allow the user to investigate the total envelope of opportunity.

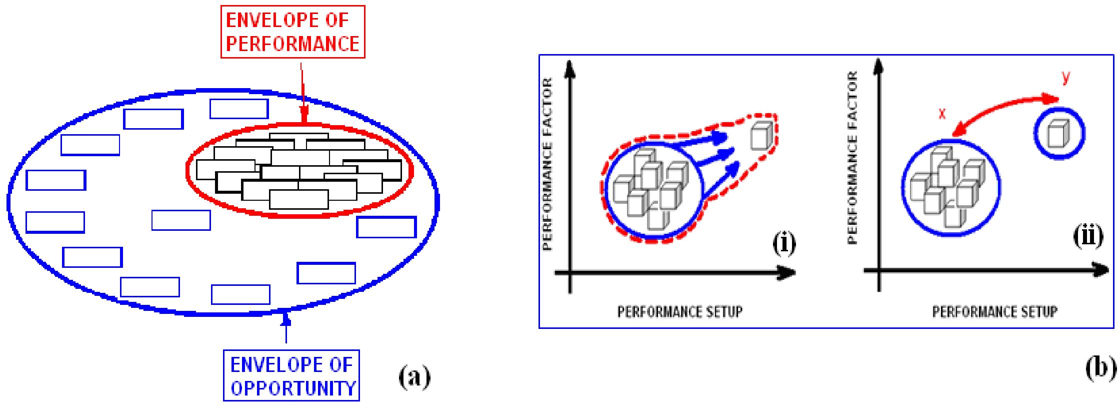


Figure 9.3 Processing envelopes

It has also been considered how such envelopes are to be utilized (Matthews *et al, 2006d)*:

- Engineers can either look at ways to develop the flexibility of the existing design so it can cope with the variant product, that is increasing the performance envelope, as with figure 9.3bi, this gives the envelope of opportunity the total flexible range of the system, or,
- More drastically the performance envelope can be shifted to encompass the new product, changing its configuration, but not giving the flexibility to produce the existing products moving from x on figure 9.2bii to y, or
- The system can be designed, so that *change parts* can be employed to reconfigure the design, and hence allow the design envelope to encompass the new product. This moves from x to y, but leaves the option to move back to x.

In addition to these, failure mode maps (FMMs) have been presented (cf. figure 9.4b). These, build on the envelopes of opportunity and performance (figure 9.4a); converging on areas of functionality where the machine can be altered with no failure being invoked, but also present the failure mode(s), when a design solution lies outside the functional area. The generation of FMMs allows the designer to assess which failure modes are restricting a solution variant. With this knowledge the designer can assign the variant product to a functional area where the failure mode is not violated, or modify the design to nullify the failure mode (Matthews *et al,* 2007c).

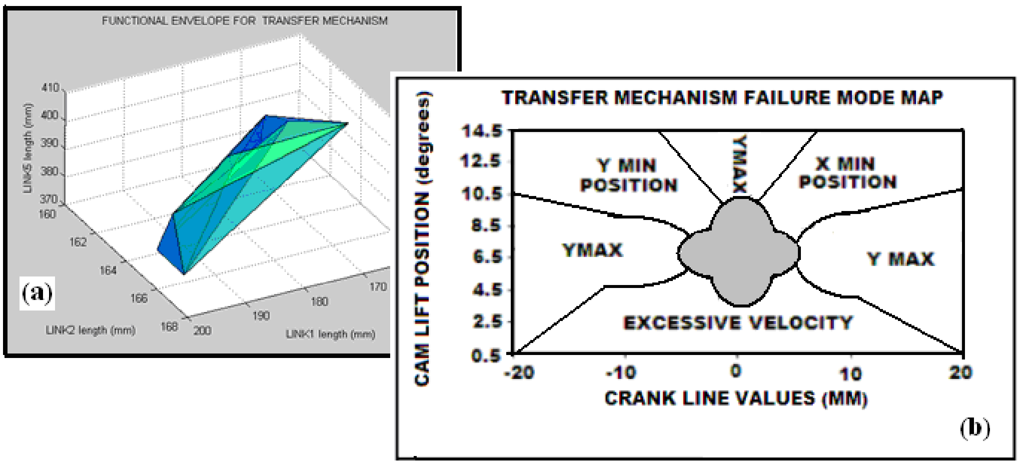


Figure 9.4 Processing ability representations

9.1.5 Assessment of machines processing ability

Chapter 7 encapsulates the work from the previous chapters and describes how the constraint-based approach to finding the performance and opportunity envelopes of processing machines can be employed and implemented. The approach was shown graphically in the flowchart figure 7.2.

9.1.6 Validation of approach

To demonstrate the approach presented in chapter 7, it was successfully implemented on three case studies, where the inherent capability (performance envelope) and potential capability (opportunity envelope) have been assessed:

1. A confection packaging machine: where the manufacturer would like to investigate to capability of the existing machine to process a larger product.
2. An overwrapping packaging machine: where the manufacturer has to pack a different product with a new packaging film, and needed to identify if this was possibly.
3. A case packing machine: where the manufacturer wants to pack a different product into a new product into a new optimal pack configuration, and identify if the existing machine configuration was capable. These have been presented in chapter 8.

9.2 SUMMARY

The work presented in this thesis has successfully proven that the following three hypotheses are true; namely that:

- A generic process can be formed to identify the limiting factors (constraints) of variant products to be processed (Matthews *et al,* 2006c).
- The identified limiting factors (constraints) can be mapped to form the potential limits of performance for a system (Matthews *et al,* 2007b; c).
- The limits of performance of a system (performance envelopes), can be employed to assess the design capability to cope with product variation (Matthews *et al,* 2007a; b).

9.2.1 The specific outcomes of the new approach have been:

- It allows the envelopes of performance and opportunity of a given machine to be investigated. Therefore assessing the inherent and potential capability of the machine (Matthews *et al,* 2007c).
- It offers the opportunity to investigate the potential redesign of a machine to handle product variation (Matthews *et al,* 2007a).
- It offers the ability to represent failure modes into a constraint-based simulation/ model (Matthews *et al,* 2006c).
- Allows simple sensitivity analysis to be performed on a design (Matthews *et al,* 2006d).
- The holistic Constraint-based approach offers the possibility to optimize a design when resources are in conflict (Matthews *et al,* 2007a).

9.3 FUTURE WORK

The thesis has presented a volume of research which has been disseminated in a number of peer reviewed journal and conferences. These can be seen in appendix F. This research has also identified areas where further research could be carried out. These are separated into long and short term possibilities.

9.3.1 Short term

9.3.1.1 Equipment types

The emphasis of the work presented in this thesis has been conducted on discrete mechanical performance. Although, this covers a large proportion of the manufacturer equipment employed worldwide, it does not consider much of the termed process technologies i.e. agglomeration as used in the food industry. To offer a more complete solution for product variation analysis the approach must be extended to deal with more continuous flow type applications.

9.3.1.2 Product analysis

A lesson learned in this research, comes from the fact that, it is the product variation that drives the need for the approach. Beyond the understanding of the constraints that initially bound the manufacturing equipment. It is the interaction of the product constraints with the process that is more important. At this stage there is no formal approach to define or analyse these process product interactions. Further research is required to address this deficit.

9.3.2 Long term

9.3.2.1 Knowledge retention

This implementation of the approach established in this thesis, opens the opportunity of redesigning the original machine so as to maximize its allowable design space. However, such an approach, specifically the redesign activities can not be carried out efficiently in many in an industrial environment; the inhibiting factors to this include the following:

- It requires expertise and significant time for new design engineers to understand a machine. Current representations for machines, i.e. various product models, mainly provide geometrical and topological information, such as assembly relationships, shapes and dimensions. These lack necessary information for redesign tasks, such as performance capabilities and constraint rules.
- Previous redesign processes, including design activities, decisions-made and corresponding rationale, are still recorded in text documents (e.g. design reports, meeting minutes) and even retained in employees' memory. It is difficult for new design engineers to assimilate and digest these redesign processes.
- Over time, it becomes impossible to retrace the engineering reasoning and decision making processes which have taken place during any design/redesign process.

While the approach presented in this thesis is applied, an array of information is developed about the product, process and their interaction. This is useful information for both the manufacturer and the producer. Methods need to be developed for the long term retention of this information, for future redesigns or developments in respect of, other potential product variants.

9.3.2.2 Software

The constraint modeller employed in this research (Mullineux, 2001) has many built-in functions as described in chapter 5. The approach described in this thesis utilizes these combinations of these functions, which the user must program. It could be useful in an industrial environment if the approach could be partially pre-programmed, so only the relationship constraints need be changed.

9.4 CONCLUDING REMARKS

While showing the three hypothesis are true. This research has contributed to existing knowledge: as it offers the producers of products, a new approach to, and a different understanding of the analysis and redesign of manufacturing equipment, when it is required to process a new or variant product. Currently, companies face the unprecedented challenges of the global marketplace. Manufacturers are force to continually vary their existing products to stay competitive. Many of these variations arise over short periods due to marketing and customer demands. Some products are stable over long periods whilst others are short lived or seasonal. An approach to investigate the capability of existing equipment to handle this variation has been presented in this thesis. Although the approach has been targeted at existing equipment, it is also applicable as a support tool for the design activities of new equipment. In conclusion to this thesis the following statement can be made:

"It is possible to map the limiting factors (Constraints) of equipment and of a variant product, to generate performance envelopes which can be employed to assess the design capability of the equipment to cope with product variation"

APPENDIX A

In this section the full code for the ejection mechanism case study is shown and annotated.

Ejection mechanism program

```
$..Optimizer setup section......................................

optmethod(5);
setopt(200,0.00001,0.00001,0.00001,1.0);

$..declaration section..........................................

dec mod3 world;
dec mod3 m1, m2,m3,m4,m5,m6,m7,m8,push_cam;
dec geom camf1, camf2, link;
dec geom sweet,ejectarm_end,pushrod_body,clash, clash1;
dec geom pushrod, ejectarm, pushrod1,clash2;
dec geom pushrodlg, camf2lg, linklg,linkst,pos1,half;
dec geom fr1,fr2,fr3,fr4,frame;$...machine frame.
dec geom ol1,ol2,ol3,ol4;$...max and mins of arm travel.
dec geom cam1,cam2,cam3,cam4,cam5;
dec geom camln,camln1,camln2,camln3;
dec geom p1,p2,p3,p4,p5;
dec int flag,flag1,flag2,flag3,flag4,flag5,minflag1,flag6;
dec int ii,vol,vol1,vol2,vol3,vol4,vol5,vol6;
dec int npoint,hope,hope1,hope2,hope3,hope4,hope5,erro;
dec int min_vol, min_vol1,opp,opp1,opp2,opp3,opp4;
dec real td,x,y, trooth, trooth1,gold,gold1,gold2;
dec real xmax, xmin, xcurrent,ymax,ymin,ycurrent;
dec real test1, test2;
dec real gscx, gscy, gsca;
dec real cgvx[npoint], cgvy[npoint], cgva[npoint];
dec real vv_x[1], vv_y[1];
dec real vv_vals[1,3];
dec real period;
npoint=4;
period=25;
dec real px[npoint],py[npoint],abc;
dec real ax[npoint],ay[npoint];
dec geom qq[npoint];

$..Varible pre-valuing section..................................

pushrodlg = 385;
camf2lg = -170;
linklg = -165;
xmax,ymax = -9999, -9999;
xmin,ymin = 9999, 9999;
opp,opp2 = 9999, 9999;
flag,flag1,flag2,flag3,flag4,flag5,flag6 = 1,1,1,1,1,1,1;
hope = camf2lg;
hope1 = pushrodlg;
hope2 = linklg;
td=1/36;
```

```
$..Setup.section...............................................

function setup
{
   world = mod3(0,0,0,0,0,0);
   p1 = pnt(0,0,0,world);$............cam follower arm pivot
   p2 = pnt(-103,395,0,world);$.......Cam follower point
   p3 = pnt(-110,0,0,world); $........cam centre visual referenece
   p4 = pnt(-110,44,0,m1);$...........cam follower visual reference
point
   cfont(7,p1,p2);


   m1 = mod3(0,0,0,0,0,0,world); $...........World model space
   camf1 = lin(0,0,0,-110,44,0,m1); $........Cam follower part1
   camf2 = lin(-110,44,0,camf2lg,20,0,m1);$..Cam follower part2

   m2 = mod3(0,0,0,0,0,0,world);$..Link and ejection arm model space
   link =lin(linklg,pushrodlg,0,-105,395,0,m2);$..Link element
   ejectarm = lin(-105,395,0,-25,258,0,m2);$>ejection arm element
   pivot(m2,link:e2,p2);

   ejectarm_end = translate(-25,258,0)*cyl(10,10);$ Arm solid
   ejectarm_end:m = &m2;
   ccol(blue(),ejectarm_end);


   ccol(yellow(),p1,p2,p3,fr1,fr2,fr3,fr4);
   ccol(blue(),link);
   ccol(blue(),ejectarm);

   m3 = mod3(0,0,0,0,0,0,m1); $pushrod model space
   pushrod =  lin(0,0,0,0,pushrodlg,0,m3);$.. pushrod element
   pivot(m3, pushrod:e1,camf2:e2);
   ccol(blue(),pushrod);

   m5 = mod3(0,0,0,0,0,0,world); $frame model space
   frame= translate(-196,305,0)*blk(36,60,20);
   frame:m = &m5;
   ccol(blue(),frame);


   m8 = mod3(0,0,0,0,0,0,m3); $push rod body model space
   pushrod_body = blk(5,200,5,m8);
   pushrod_body = translate (0,275,0)*pushrod_body;
   pushrod_body:m =&m3;
   ccol(blue(),pushrod_body)


   pivot(m1,camf1:e1,p1); $cam follower main  pivot
   ccol(blue(),camf1, camf2,p4);
   cfont(0, p3);
   cfont(6, p4,p5);
   $cfont(4,ejectarm,link,pushrod,cam1);

   sweet = translate(-89.142,237.114,0)*cyl(10,10); $..sweet solid
   sweet:m =&m6;
   ccol(blue(),sweet);


}



$.....cam section..............................................
function cam
{
push_cam = mod3(-110,0,0,0,0,0,world);
cam1 = crv (36,2, push_cam);
```

```
cdegree(cam1, 5);
camln =lin(55.5,0,0,-55.5,0,0,push_cam);
camln1 = lin(55.5,0,0,55.5,0,-10,push_cam);
camln2 = lin(55.5,0,-10,-55.5,0,-10,push_cam);
camln3 = lin(-55.5,0,-10,-55.5,0,0,push_cam);
 fopen (1,1,"E:\programmes\macros\cam1.dat"); $.file saved on home
directory
$fopen (1,1,"\\rumba\homes\dos\macros\cam1.dat"); $.file saved on home
directory

     loop (ii,0,35)
    {
     freadln(1,td,x,y);
     ckdiff(cam1,ii,td);
     cpoint(cam1, ii,x,y);
    }

ccol(blue(),cam1,camln,camln1,camln2,camln3);
fclose(1);
}

$..ASSEMBLY section..(constraint optimization)....................


function assemble

{
   var m1:az, m2:az, m3:az;$ Optimization varables

   rule = (pushrod:e2 on link:e1);$ pushrod to link constraint

   rule = (camf1:e2 on cam1); $ Camfollwer on cam constraint


}


$..CYCLE section....Mechanism motion section................


function reset

   flag, flag1,flag2,flag3,flag4,flag5,flag6 = 1,1,1,1,1,1,1;
   pushrodlg = 385;
   camf2lg = -170;
   linklg = -165;

   hope = camf2lg;
   hope1 = pushrodlg;
   hope2 = linklg;

   xmax,ymax = -9999, -9999;
   xmin,ymin = 9999, 9999;
   opp,opp2 = 9999, 9999;

   erro = 0;
   setup();
   assemble();
   rpnt();
}


function cycle
{

dec int code;
dec real ahold ,step;
ahold= push_cam:az;
dec int i;
```

```
step = 360/npoint;
fopen( 3, 2, "pos.dat" );
vol = volume(ejectarm_end);
vol1 = volume(sweet);
vol4 = volume(pushrod_body);
vol5 = volume(frame);



   loop (i,0,npoint)
{
      push_cam:az = ahold +i* step;
      assemble();
      qq[i] = transf( ejectarm:e2);
      ccol(cyan(),qq[i]);
      cfont(5, qq[i]);
      rpnt(1);
      px[i] = qq[i]:x;
      py[i] = qq[i]:y;
      xcurrent = px[i];
      ycurrent = py[i];
      if( flag < 1)
        {

         fail();
        }

      pushrod_body:m =&m3;

      clash = sweet - ejectarm_end ;
      clash:m= &m6;
      clash1 = frame - pushrod_body ;
      clash:m= &m4;


      vol2 = volume(clash);

      opp = vol2;
      if  (opp < opp2)
      {opp2 = opp;
      }

      vol3 = volume(clash1);


      fwriteln (3,px[i],",",py[i],opp,vol2);

      minflag1 = min(flag1);
      xmax = max(xmax,xcurrent);
      xmin = min(xmin,xcurrent);
      ymax = max(ymax,ycurrent);
      ymin = min(ymin,ycurrent);
      gold = max(px[npoint]);
      gold2 = px[npoint/2];
      trooth1 = truth();
      trooth = max(trooth1);

 fwriteln(0,"xmax=",xmax,",xmin=",xmin,",ymax=",ymax,",ymin=",ymin);
 fwriteln(0,"max truth value =",trooth);



$..Failure MODE Detection subsection.(CONSTRAINT MONITORING).......
   if (vol3 < vol5)
      {
      flag1 = 0;
      fwriteln(0,"**MECHANISM FAILURE** FRAME CONTACT**");
      }
```

```
     if( opp2 < 500)
       { flag2 = 0;
          fwriteln(0,"**MECHANISM FAILURE**EJECTARM TO SWEET
CONTACT**");
         }

     if(gold >-120)
      { fwriteln(0,"**MECHANISM FAILURE**REST POSITION**");
        flag3 = 0;
            }$.....Eject arm saftey position.

    if(gold2  < -100)
      { fwriteln(0,"**MECHANISM FAILURE**MAX point mechanism
clash**");
        flag4 = 0;
      }$.....Eject arm saftey position.

   if( trooth >.2 )
      { fwriteln(0,"**MECHANISM FAILURE**TRUTH**");
        flag5 = 0;
            }$.....mechanism assembly truth.

      if (xmin  < -135)
      {
      flag6 = 0;
       fwriteln(0,"**MECHANISM FAILURE** FRAME TO EJECTARM
CONTACT**");
       fail();
      }

  flag = flag1 * flag2 * flag3 * flag4 * flag5* flag6;
      fwriteln(0, flag1, flag2, flag3, flag4, flag5,flag6);
        fwriteln(0,"pushrod =",hope1,"link=",hope2,"camfl=",hope) ;

      }
push_cam:az =ahold;
fclose(3);

}
function fail

{
      fwriteln(0,"**MECHANISM FAILURE**") ;
      fwriteln(0,"Individual increase/decrease failure limit
=",erro,"mm") ;
      fwriteln(0,"final dimensions of ","pushrodlg =
",hope1,",camf2lg= ",hope,",linklg= ",hope2);

}


function step

{

assemble();
vol = volume(ejectarm_end);
vol1 = volume(sweet);
vol4 = volume(pushrod_body);
vol5 = volume(frame);


      qq[1] = transf( ejectarm:e2);
      ccol(cyan(),qq[1]);
      cfont(5, qq[1]);
      rpnt(1);
      px[1] = qq[1]:x;
      py[1] = qq[1]:y;
      xcurrent = px[1];
```

```
      ycurrent = py[1];
      assemble()
      clash = sweet - ejectarm_end ;
      clash:m= &m6;
      clash1 = frame - pushrod_body ;
      clash:m= &m4;

      vol2 = volume(clash);
      show vol2;
      if( vol2< vol)
      { show"CLASH";
      }

      vol3 = volume(clash1);
      show vol3;
      if (vol3 < vol5)
      {
         show"CLASH1";}

rpnt();


}



function arm_disp $displacement graph

{
   dec int f;
   graph(0);
   gcurve(0,1);
   gcolour(red(),1);
   gtitle("Eject Arm Displacement");
   gxcaption( "x displacement" );
   gycaption( "y displacement" );
   gxscale(-130,-60,10);
   gyscale(236,241,1);
   loop(f,0,npoint)
   {gdata(0,f,px[f]);
   gdata(1,f,py[f]);
   }
   grpnt();
}



function acc_graph $acceleration graph

{
   dec int i;
   ax = deriv (2,px,0.1);
   ay= deriv(2,py,0.1);
   graph( 0 );
   gcurve(0,1);
   gcolour(red(),1);
   gtitle("Acceleration");
   gxscale(0,npoint,npoint/4);
   gyscale(0,100,5);
   loop(i,0,npoint)
   {gdata(0,i,i);
     gdata(1,i,sqrt((ax[i])^2=(ay[i])^2));
   }
   grpnt();
}


function increase $parametric variation 1
{
```

```
 while(flag == 1)
   {
    hope = hope - 1;
    camf2lg = hope;
    setup();
    assemble();
    cycle();
          }
erro = camf2lg;
fail()

}

function increase1 $parametric variation 2

{

 while(flag == 1)
   {
    hope1 = hope1 + 1;
    pushrodlg = hope1;
    setup();
    assemble();
    cycle();
          }
erro = pushrodlg;
fail()
}

function increase2$ Parametric variation 3

{

 while(flag == 1)
   {
    hope2 = hope2 - 1;
    linklg = hope2;
    setup();
    assemble();
    cycle();
          }
erro = linklg;
fail()

}


function decrease $ parametric variation 4

{
 while(flag == 1)
   {
       hope = hope + 1;
    camf2lg = hope;
    setup();
    assemble();
    cycle();
          }
erro = camf2lg;
fail()

}
function decrease1 $ parametric variation 5

{
 while(flag == 1)
   {
    hope1 = hope1 - 1;
```

```
    pushrodlg = hope1;
    setup();
    assemble();
    cycle();
          }
erro = pushrodlg;
fail()
}

function decrease2 $parametric variation 6

{
 while(flag == 1)
   {

    hope2 = hope2 + 1;
    linklg = hope2;
    setup();
    assemble();
    cycle();
          }
erro = linklg;
fail()
}


function decrease3 $parametric variation 7

{
 while(flag == 1)
   {
       hope2 = hope2 + 1;
    linklg = hope2;
     hope1 = hope1 - 1;
    pushrodlg = hope1;
    hope = hope + 1;
    camf2lg = hope;
    setup();
    assemble();
    cycle();
          }
fail()
}

function increase3 $parametric variation 8
{
 while(flag == 1)
   {
    hope2 = hope2 - 1;
    linklg = hope2;
     hope1 = hope1 + 1;
    pushrodlg = hope1;
    hope = hope - 1;
    camf2lg = hope;
    setup();
    assemble();
    cycle();
          }
fail()
}


$.......mechanism function windows............................


function op_envelope $ bounded box construction

{
    ol1 = lin(xmin,ymin,0,xmax,ymin,0,m4);
```

```
    ol2 = lin(xmax,ymin,0,xmax,ymax,0,m4);
    ol3 = lin(xmax,ymax,0,xmin,ymax,0,m4);
    ol4 = lin(xmin,ymax,0,xmin,ymin,0,m4);

rpnt();

}

$..GUI setup section............................................

setup();
cam();
assemble();
graphics();
rpnt();
zoom();
zoom(0.8);
background(1,1,1);
deflight();
rpnt();

$..GUI BUTTONS SECTION.......................................


menu buttons

{

    button CYCLE
   { cycle();
   }

   button RESET
   { reset();
   }

    button DRAW ACC GRAPH
   {acc_graph();
   }


    button OPERATIONAL WINDOW
   {op_envelope();
   }


    button STEP
   {step();
   }

   button DRAW ARM DISP GRAPH
   {arm_disp();
   }

 submenu  MULTIPLE ELEMENT CHANGE >

   { button  decrease elements
     {
      decrease3()
     }

     button  increase elements
     {
      increase3()
     }
    }
submenu SELECT ELEMENT CHANGE>

   { button  Cam follower length increase
```

```
      {
       increase()
      }

      button  pushrod length increase
      {
       increase1()
      }

      button  link length increase
      {
       increase2()
      }

      button  Cam follower length decrease
      {
       decrease()
      }

      button  pushrod length decrease
      {
       decrease1()
      }

      button  link length decrease
      {
       decrease2()
      }

    }

}
remmenu();

addmenu( buttons );
```

APPENDIX B

Function name	Syntax	Description	Usage in Thesis
BLK	blk(<x>, <y>, <z>[,<model>]);	This function returns an object of type geom. which represents a solid object. (This object is a block).	Used to check for collision failure mode constraints
BUTTON	button <name> \n { ... \n } \n	This defines the basic parts of a menu. Button commands are found within blocks for menu and submenu commands.	Used for visualizations and user interface
CYL	cyl(<radius>, <height>[, <model>]);	This function returns an object of type geom which represents a solid object which is a cylinder.	Used to check for collision failure mode constraints
GRAPH	graph(<code>);	This function creates a graph window.	Used for visualizations
BOUNDLOWER	boundlower(<value>, <var1>[, <var2>, ...]);	This function sets the lower bound of one of more variables.	Used in the optimization and construction of mechanisms
BOUNDUPPER	boundupper(<value>, <var1>[, <var2>, ...]);	This function sets the upper bound of one of more variables.	Used in the optimization and construction of mechanisms
BACKGROUND	background(<code>)	This function is used to set the background colour for a graphics window.	Used for visualizations
CDEGREE	cdegree(<curve>, <degree>)	This sets the degree of the given curve to the given value.	Used in the construction of cams
CDERIV	cderiv(<curve>);	This returns a new object of type geom which represents the curve which is the derivative of the original one.	Used in the construction of cams
CFIT	cfit(<curve>, <code>, <t_array>, <p_array>[, <i_array>]);	This is used to create the control points for a curve so that it passes between given points. as components of the points and as many rows as there are points.	Used in the construction of cams

CKDIFF	ckdiff(<curve>, <position>, <value>);	This sets (or changes) the knot difference of the given curve at the given position to be the given value.	Used in the construction of cams
CPOINT	cpoint(<curve>, <position>, <x>[, <y>[, <z>]]);	This sets (or changes) the control point of the given curve at the given position to be the point given by the remaining arguments.	Used in the construction of cams
CRV	crv(<ncontrol>, [<type>, [<model space]]);	The crv function returns an object of type geom which represent a free-form curve. The curve has the form of a (closed) B-spline.	Used in the construction of cams
DEC	dec <variable_type> <variable_name>;	The command is used to declare a variable in the macro language.	Used in the optimization and construction of mechanisms
DERIV	deriv(<n>, <array>, <increment>[, <code>]);	This function evaluates first or second derivatives numerically.	
FREAD	fread(<unit>, <var1>[, <var2>, ...]);	This function is used to read input from a file.	Used to input data into the models
FUNCTION	function udf_name \n { [dec command] \n [inp command] \n [var command] \n [out command] \n statements \n } \n	The function command starts a user defined function (udf). It is followed by the name of the udf being created. This mustn't be a reserved word or an existing variable name. If it is an existing udf name, then that udf is redefined.	Used in the optimization and construction of mechanisms
FIX	fix(<var1>[, <var2>, ...]);	This function fixes the value of one or more variables so that the optimisation procedures cannot change them.	Used in the optimization and construction of mechanisms
FOPEN	fopen(<unit>, <access>, <file name>);	This function attempts to open the given file with the appropriate access, and assign it to the logical unit number.	Used to open output files for the analysis of designs

GEOM	dec geom <variable_name>[, <variable_name>, ...];	This provides the type for a geometry variable declaration. The variable is not specific to a particular form of geometry but is a general variable.	Used in the construction of mechanisms
GRAPHICS	graphics();	This creates a new graphics window.	Used to setup visualizations
LIN	lin(<x1>, <y1>, <z1>, <x2>, <y2>, <z2>[, <model space>]);	This function returns an entity of type geom which represents a line. The arguments give the coordinates of the ends of the line. The optional last argument gives the model space in which the line lies. If this is present, then the coordinates are local to that space.	Used in the construction of mechanisms
LOOP	loop(<variable>, <start>, <end> [,<step>]) \n { commands \n } \n	The loop command allows a block of code within the braces to be evaluated a number of times. If the step value is omitted, a value of unit is assumed. The step value can be positive or negative (but not zero).	Used in optimization and construction of mechanisms and their motion
MOD2	mod2(<x disp>, <y disp>, <rotation> [,<model space>]);	This type defines a two-dimensional model space within SWORDS.	Used in the construction of mechanisms
MOD3	<mod3space> = mod3(<x disp>, <y disp>, <z disp>, <x rot>, <y rot>, <z rot> [,<model space]);	This type defines a three-dimensional model space within SWORDS.	Used in the construction of mechanisms
OPTMETHOD	optmethod([<method number>]);	This function sets the optimisation method used when the system searches to satisfy constraints. This happens in user defined function (udf's) and in constraint groups.	Used in optimization and construction of mechanisms
ON	<ent1> on <ent2>	This is a "binary" function. It finds the distance between two geometric entities.	Used in optimization and construction of mechanisms
PNT	pnt(<x>, <y>, <z>[, <model>]);	This function returns an entity of type geom which represents a point.	Used in construction of mechanisms

PIVOT	pivot(<model space>, <point1>, <point2>);	This function is used to pivot one model space onto another space higher up in the model space hierarchy (nearer the world space). .	Used in construction of mechanisms
RULE	rule(<expression>);	This command specifies a rule (or constraint) that the user wishes to be made true. The expression is any valid algrabraic expression involving defined variables functions. The value of the expression is treated as a real number. It should be zero when it is true. The absolute value of the expression is effectively a measure of its falseness.	Used in optimization and construction of mechanisms
SETOPT	setopt([<iter>[, <truth>[, <qtruth>[, <minstep>[, <initstep>]]]]]);	The setopt function is used to modify the default control values for the optimization module from within a SWORDS macro.	Used in optimization and construction of mechanisms
SLID	<flag> = slid(<model1>, <model2>, <d1> [,<config> [,<delta]]);	This function is used to solve for a sliding joint directly by the geometry without having to perform any optimisation. The solution is effectively the intersection of a line and a circle.	Used in construction of mechanisms
TRANSF	transf(<geom>[, <model]);	This function is used to transform a geometric entity into world space or into another model space. A copy of the entity is returned by the function lying in the appropriate space and coincident with the given object.	Used to import solids and end effector points for analysis
TRUTH	truth()	This function returns the truth value resulting from the last optimisation search. The value returned is the square root of the sum of the squares of the last set of rule values.	Used to check for mechanism deconstruction and incorrect construction failure modes

VAR	var <var1>[, <var2>, ...];	This command specifies the variable entities for a user defined function.	Used in optimization and construction of mechanisms
VOLUME	volume(<body>);	This function returns a single value which is the volume of the given body.	Used to check for collision failure mode constraints
WHILE	while(<logical expression>) \n { commands \n } \n	This statement repeatedly executes a block of code while the expression is true. It is a more general case of the loop command.	Used for failure mode checking while mechanism/ machine is in motion.

APPENDIX C

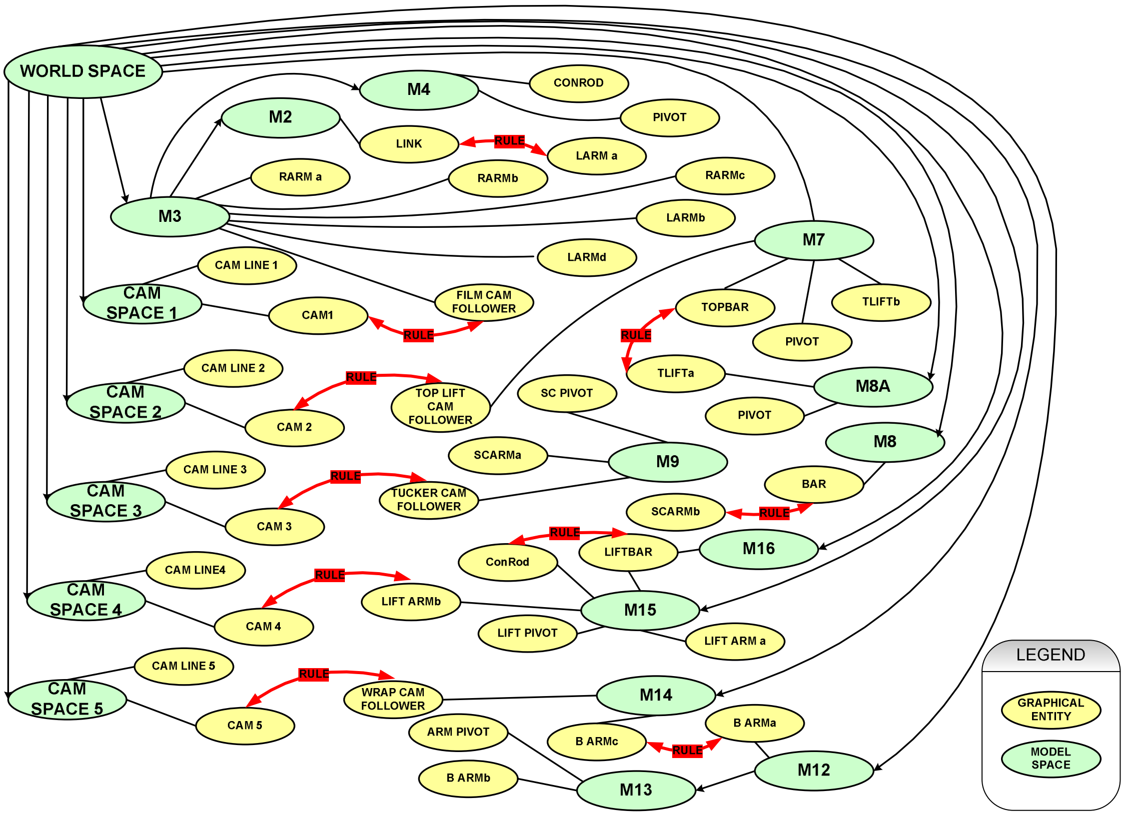


Figure C1 Model space hierarchy for basic transmission mechanism (Case study 2)

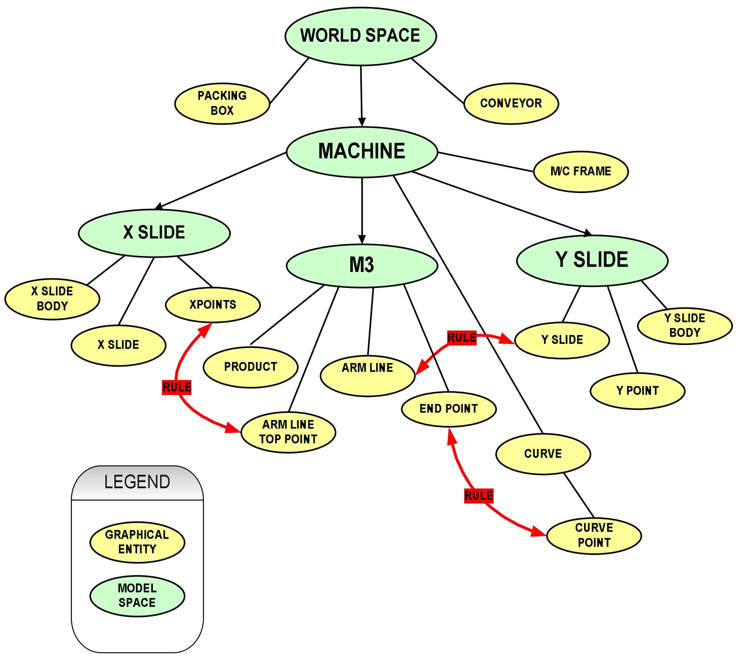


Figure C2 Model space hierarchy for basic pick-and-place model (Case study 3)

APPENDIX D

D1 Product motion constraints

To identify the constraints associated with the product, a simple test fixture was constructed (figure D1) so variation in weight package film and surface finish could be tested. A 'knobbly' surface was manufactured by polystyrene to replicated the cauliflower. Three different films have been tested, each with the flat as well as with the knobbly surface, from a product weight of 2 pounds in 0.5 pound steps up to 5 pounds. At this stage the exact characteristics of the tested foils are unknown, so that they just will be termed by there product names: JC, Cadons and Sandiacre. A serial robot was used to produce motion. To consider the directionality of the movement, data has been collected for the straight and the 45° move.

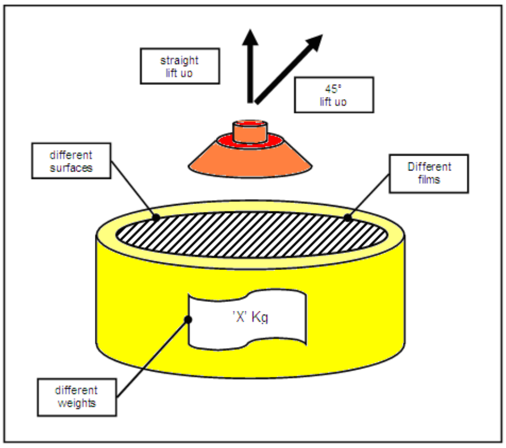


Figure D1 Test fixture

The experiments were carried out as follows. For all the combinations of the investigation factors: weight, surface condition, package material and movement direction the test piece was accelerated to the maximum speed of the robot, and it was observed if the product got lost during the motion or not. In case of failing the test the speed was reduced in steps and the experiment was repeated until it was passed successfully. Hence a specific combination of investigation factors could be linked to the maximum speed up to which the test piece can be accelerated. In separated test runs the acceleration of the robot for each of the different speeds was explored, with the help of an accelerometer, to link these sought data to the prior found results. For all the test points that reach this limit.

Figure D2 Robot setup

Results of the test runs distribute in a certain area and that they should just be used as an indication with an additional safety factor to estimate the real performance limit. The experiments with a flat surface of the test piece are better repeatable and more stable than the ones with knobbly surface conditions. If the film is not clamped taut, an exact forecast of the results is difficult due to the fact that it greatly depends an the kind and the degree of surface irregularities if the product can be sucked smoothly. This leads to the first conclusion that the surface condition is one of the most important factors which have to be considered and that when handling products with uneven surface, a greater safety factor is required to guaranty a stable process. Nevertheless it should be tried to characterise and to investigate different kinds and levels of surface irregularities in an additional research work to get a better understanding of the exact factors which limit the capability to suck a product.

Without any doubt the weight of the product is a crucial value that limits the performance of the pick-and-place process. But the effect of a gain in weight is unproblematic to forecast, because there seems to be an almost proportional behaviour in parts of the curves.

However, in connection with the weight of the products two additional points of consideration could be observed during the test work. Firstly, it is absolutely important to pick up the item at the centre of gravity to avoid that it peels off the suction cup sidewise while lifting it up. This becomes also crucial when quick motions are applied because the mass might move inside the package due to its inertia and so does the centre of gravity. Secondly, the combination of a heavy test piece and fast movements leads to uncontrollable swinging motions of the product which could create difficulties in placing the product precisely.

Results

Table D1 Knobbled surface lifting

Film:	**JC**						
Weight [lb]:	2	2.5	3	3.5	4	4.5	5
Surface:	knobby	knobby	knobby	knobby	knobby	knobby	knobby
Speed max [cm/min]:	9000	5000	4000	3500	2000	1000	1000
Speed max [m/s]:	1.50	0.83	0.67	0.58	0.33	0.17	0.17
a max [m/s^2]:	10.95	9.55	7.13	5.07	3.34	2.18	2.18
Film:	**CADONS**						
Weight [lb]:	2	2.5	3	3.5	4	4.5	5
Surface:	knobby	knobby	knobby	knobby	knobby	knobby	knobby
Speed max [cm/min]:	8000	4500	4000	3000	2000	1000	1000
Speed max [m/s]:	1.33	0.75	0.67	0.50	0.33	0.17	0.17
a max [m/s^2]:	10.95	8.01	7.13	4.47	3.34	2.18	2.18
Film:	**SANDIACRE**						
Weight [lb]:	2	2.5	3	3.5	4	4.5	5
Surface:	knobby	knobby	knobby	knobby	knobby	knobby	knobby
Speed max [cm/min]:	9000	7000	5000	4000	3000	2000	1000
Speed max [m/s]:	1.50	1.17	0.83	0.67	0.50	0.33	0.17
a max [m/s^2]:	10.95	10.71	10.71	7.13	4.47	3.34	2.18

Table D2 Flat surface lifting

Film:	**JC**						
Weight [lb]:	2	2.5	3	3.5	4	4.5	5
Surface:	flat	flat	flat	flat	flat	flat	flat
Speed max [cm/min]:	9000	9000	9000	4500	4000	3000	2000
Speed max [m/s]:	1.50	1.50	1.50	0.75	0.67	0.50	0.33
a max [m/s^2]:	10.95	10.95	10.95	8.01	7.13	4.47	3.34
Film:	**CADONS**						
Weight [lb]:	2	2.5	3	3.5	4	4.5	5
Surface:	flat	flat	flat	flat	flat	flat	flat
Speed max [cm/min]:	9000	9000	9000	4500	4500	3000	2000
Speed max [m/s]:	1.50	1.50	1.50	0.75	0.75	0.50	0.33
a max [m/s^2]:	10.95	10.95	10.95	8.01	8.01	4.47	3.34
Film:	**SANDIACRE**						
Weight [lb]:	2	2.5	3	3.5	4	4.5	5
Surface:	flat	flat	flat	flat	flat	flat	flat
Speed max [cm/min]:	9000	9000	9000	5000	4000	3000	3000
Speed max [m/s]:	1.50	1.50	1.50	0.83	0.67	0.50	0.50
a max [m/s^2]:	10.95	10.95	10.95	9.55	7.13	4.47	4.47

The influence of the use of different films on the performance of the pick-and-place process is not that great than assumed before carrying out the experiments. The different curves of the investigation results are grouped very close together and it is difficult to decide if the slight differences are provoked by the characteristics of the foils or caused by deviations of factors that have a greater influence on the performance limit. Howsoever, film specifications that might have an influence, are the porosity and especially in case of a non flat surface the drapeabililty based on the foil material and its thickness.

D2 Path investigation using Bėzier curves

Béziers' approach to create smooth curves was used to evaluate different paths of motion between the given picking and placing point. Developed by the French mathematician in the 1970's, this concept is nowadays an important tool, used in modern drawing and CAD programs. The Bézier curves are defined by a given start and end point and a number of arbitrary control points. These variable points are located at the end of the tangents through the endpoints or the vertexes and thus defining the gradient in these points

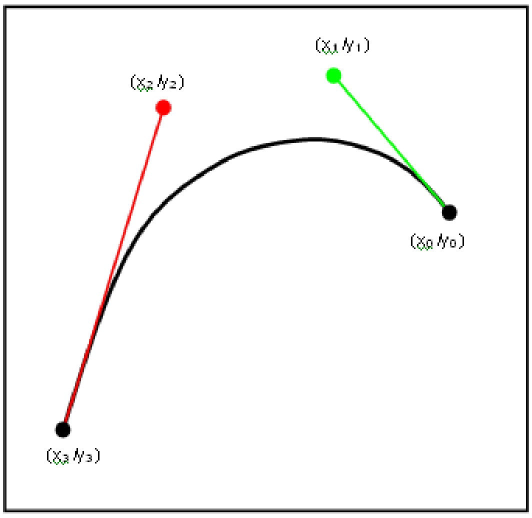


Figure D2 Curve with two control points

For the creation of the different motion paths the most common form of simple cubic equation shall be used. This is defined by the picking point (x0, y0), the placing point (x3, y3) and two control points (x1, y1), (x2, y2) which will vary from curve to curve. The equations for the two dimensional case are shown below.

$$x_{p\,i}(t) = (1\text{-}t)^3\, x_0 + 3t\,(1\text{-}t)^2\, x_1 + 3t^2\,(1\text{-}t)\, x_2 + t^3\, x_3$$

$$y_{p\,i}(t) = (1\text{-}t)^3\, y_0 + 3t\,(1\text{-}t)^2\, y_1 + 3t^2\,(1\text{-}t)\, y_2 + t^3\, y_3$$

The value for t is always in between 0 and 1 and can have any number of values. With increasing value the point defined by X(t) and Y(t) moves from the start point to the end point. To achieve a smooth curve, t will vary in 1000 steps from 0,001 to 1 in the following and thus 1000 interpolation points are created to converge the ideal curve.

D3 Finding the optimal setting

The problem which has to be solved, is to find a smooth curve between the fixed picking and placing point which provides low acceleration and hence a shot cycle time. These paths are described by cubic Bézier curves which can be altered by manipulating the two control points. With the help of an excel-sheet the bearing on the acceleration, while moving the control points, can be investigated. First of all the invariable picking and placing point as well as the two control points have to be defined. The strategy how to choose the control point will be presented later in this report. By the help of the cubic Bézier formulae and the four interpolation points a smooth curve is approximated. The factor t varies from 0 to1 in 1000 steps [0;0.001;0.002;…;0.999;1] and thus one thousand points (xp i(t) / yp i(t)) are created on the curve.

The distance gone $s(x_{p\,i}\ ,\ y_{p\,i})$ from the picking point $(x_0\ ,\ y_0)$ to each of the points on the curve $(x_{p\,i}\ ,\ y_{p\,i})$ can be calculated as following.

$$s(x_{p\,i}\ /\ y_{p\,i}) = [\ (x_{p\,i} - x_{p\,i\text{-}1})^{\ 2} + (y_{p\,i} - y_{p\,i\text{-}1})^{\ 2}\,]^{\ 1/2}$$

With the help of the constant, given velocity v the time past $t(x_{p\,i}\ /\ y_{p\,i})$ since the starting point $(x_0\,/\,y_0)$ to each point of the curve $(x_{p\,i}\ /\ y_{p\,i})$ can be calculated:

$$t(x_{p\,i}\ ,\ y_{p\,i}) = s(x_{p\,i}\ ,\ y_{p\,i})\ /\ v$$

To compare the results of the trials, the cycle time t (xp 1000 , yp 1000) is fixed to the time of one second. This is done by choosing the velocity as following.

$$v = s(x_{p\,1000},\, y_{p\,1000}) \,/\, t\,(x_{p\,1000},\, y_{p\,1000}) = s(x_{p\,1000},\, y_{p\,1000}) \,/\, 1\text{sec}$$

The acceleration $x''(t_i)$ in x direction and $y''(t_i)$ in y direction in every single point $(x_{p\,i}\,,\, y_{p\,i})$ as well as the absolute acceleration $a(x_{p\,i}\,,\, y_{p\,i})$ are approximated with the formulae below.

$$x''(t_i) = \{\, 2\,[\,(t_i - t_{i-1})\, x_{i+1} - (t_{i+1} - t_{i-1})\, x_i + (t_{i+1} - t_i)\, x_{i-1}\,]\,\} \,/\, \{\,(t_i - t_{i-1})\,(t_{i+1} - t_i)\,(t_{i+1} - t_{i-1})\,\}$$

$$y''(t_i) = \{\, 2\,[\,(t_i - t_{i-1})\, y_{i+1} - (t_{i+1} - t_{i-1})\, y_i + (t_{i+1} - t_i)\, y_{i-1}\,]\,\} \,/\, \{\,(t_i - t_{i-1})\,(t_{i+1} - t_i)\,(t_{i+1} - t_{i-1})\,\}$$

$$a(x_{p\,i} \,/\, y_{p\,i}) = [\, x''^2 + y''^2\,]^{1/2}$$

The investigation strategy is to create a number of representative curves by varying the control points (x_1,y_1) and (x_2,y_2). By comparing the maximal acceleration for the cycle time of one second of the different curves (same start and end points but variable control points) the optimal motion path with the lowest acceleration can be found.

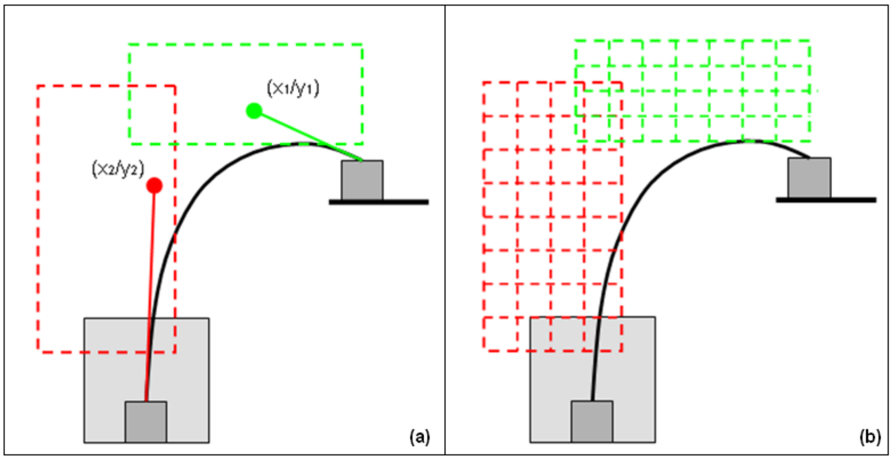


Figure D2 Control point areas

When choosing the location of the control point, constraints like the geometric boundaries have to be considered and thus these points can be varied in specific areas only. In addition the target to create a smooth and a short path of motion limits the choice of reasonable point, too. The definition of these limited areas is illustrated with the help of an example investigation later. In Figure D2a and b, the rough representative zones, where reasonable control points could be found in, are shown. Once defined these zones, lattices of selected control points are created into them and the generated curves for each combination of these control points are investigated. By repeating this procedure and creating lattices which are closer mashed, the ideal location of the control points and thus the best path can be approximated.

D4 EXAMPLE INVESTIGATION FOR POSITION H

As an example of how to find the best path of motion, the procedure for the investigation of placing position H (c.f. figure 8.17) will be presented in this paragraph in detail. For the other positions, only the results and a short description of critical issues are given. This is done because the methodology of the investigation for every single point is the same. To reduce the number of trials that have to be carried out, the area in which reasonable control points can be found should be reduced as much as possible. A number of considerations can help to reach this target. For the position of the control point (x_1, y_1), these are the following. First of all the optimal area can be reduced to the upper left hand side quadrant of the picking point because the product has to be lifted up and has to be moved to the left. By carrying out some rough investigations of different curves at the beginning of the research to get an overview, some expert knowledge could be generated which helps to reduce the area further. Basically, a curve is shorter and thus the cycle time shorter too, if the y_1 position is close to the y location of the picking point y_0. On the other hand the geometrically boundaries have to be kept in mind. The product has still to be picked up and to be moved over the edge of the conveyor before it can be lowered into the cardboard box. Consequently the curve should be as flat as possible but still has to satisfy the other constraints. That is the reason why y_1 is fixed more or less to the position of -1000 for all curves.

The x_1 location is more difficult choose on because it is partly dependent on the position of the second control point (x_2, y_2), so just a rough reasonable range $x_1 \in (-100,\dots,100)$

can be defined. The area of control point two (x_2,y_2) is harder to define in advance. The experiments have shown that to create a smooth curve with low accelerations the x_2 position should be on the left hand side of the x position of the placing point x_3. This is also important to avoid collisions with geometrically boundaries on the right hand side, such as previously placed products or the wall of the box. As shown later in detail, for the positions A,D and G these geometrical boundaries have to be considered on the left hand side as well. The product has to be placed between the wall of the box on the left and the previously placed product on the right. The curve has to move straight down at the end, to avoid a collision, in this case. That is the reason why the x_2 position for these points should not be too far to the left hand side of the placing point.

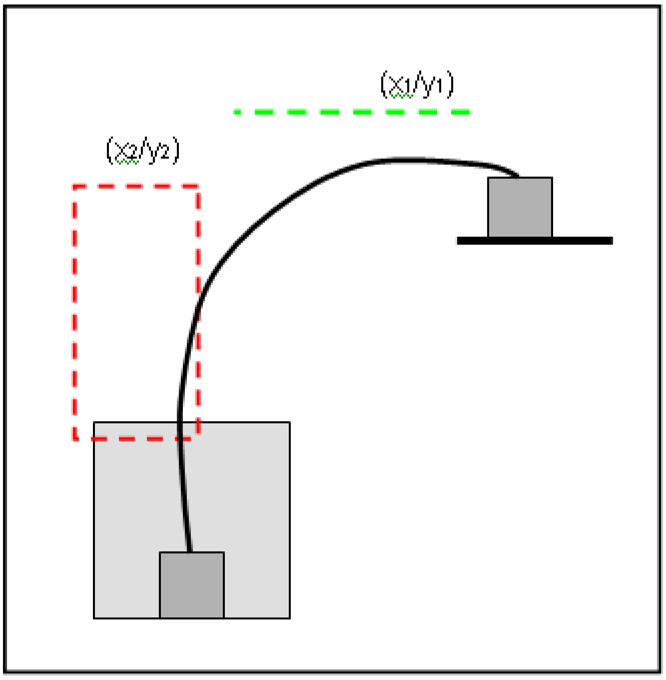


Figure D4 Control point areas for the example investigation for point H

For position H these constraints are not critical. The curve can bulge to the left to create a smoother motion. A reasonable area to test for coordinate x_2 is: $x_2 \in (-300,\ldots,-125)$. The y_2 coordinate can just be bordered roughly. The only considerations are that it should not be too low so as to create still a smooth curve and not too high to create a curve that is short. For the bottom positions (G;H;I) y_2 could range form -1100 to -1400. In figure D3 the reasonable areas for the two control points are illustrated again.

By investigating lattices of points in these zones and comparing the maximal acceleration for the standardised cycle time of one second, an ideal curve which fulfils the given constraints can be approximated.

Although possible within the constraint modelling environment, this work was undertaken in Microsoft Excel, mainly for ease of presentation. A screen shot the Excel worksheet can be seen in Figure D5.

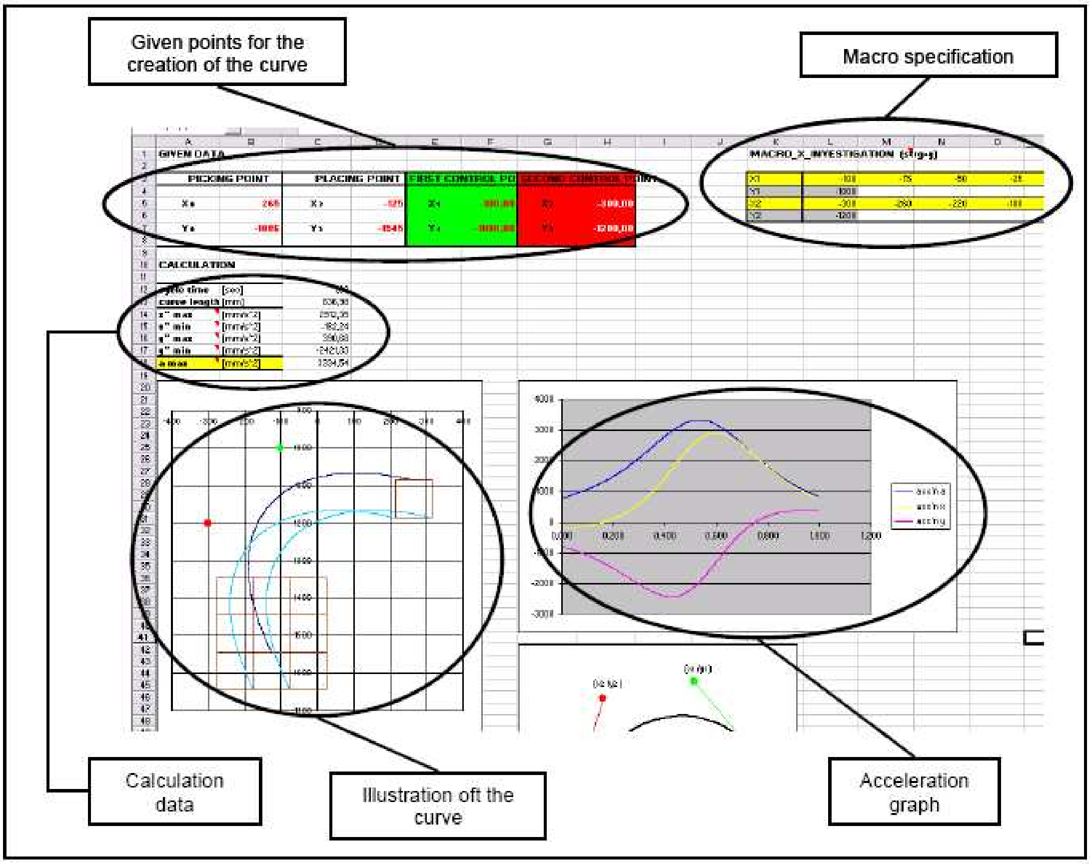


Figure D5 Screen shot of Excel tool

Appendix E

Chapter 3 gave a review of constraint-based techniques applied to the manufacturing and design engineering domains. Throughout this chapter, reference is made to the techniques that are used for constraint processing. This appendix gives a brief 'layman's' overview of these techniques and gives some relevant references where the reader can find in depth information of the processes. The constraint modeller used in this thesis predominately uses direct search methods for its optimization. This method is described in chapter 5. It is outside the scope of this thesis to critically compare these methods.

1. ***Genetic algorithms*** :(GAs) are an adaptive heuristic search algorithm premised on the evolutionary ideas of natural selection and genetic. The basic concept of GAs is designed to simulate processes in natural system necessary for evolution, specifically those that follow the principles first laid down by Charles Darwin of survival of the fittest. As such they represent an intelligent exploitation of a random search within a defined search space to solve a problem. First pioneered by John Holland in the late 1960s (Holland, 1975). Genetic Algorithms has been widely studied, experimented and applied in many fields in engineering worlds. Not only does GAs provide an alternative method to solving problem, it consistently outperforms other traditional methods in most of the problems link. Many of the real world problems involved finding optimal parameters, which might prove difficult for traditional methods but ideal for GAs.

Basic iteration

1. Randomly generate an initial population M(0)
2. Compute and save the fitness u(m) for each individual m in the current population M(t)
3. Define selection probabilities p(m) for each individual m in M(t) so that p(m) is proportional to u(m)
4. Generate M(t+1) by probabilistically selecting individuals from M(t) to produce offspring via genetic operators
5. Repeat step 2 until satisfying solution is obtained.
6. The paradigm of GAs described above is usually the one applied to solving most of the problems presented to GAs. Though it might not find the best solution. More often than not, it would come up with a partially optimal solution.

2. ***<u>Simulated annealing</u>****:* Simulated annealing (SA) is a generic probabilistic meta-algorithm for the global optimization problem, namely locating a good approximation to the global optimum of a given function in a large search space. It was independently invented by Kirkpatrick, Gelatt and Vecchi in 1983, and by Černý in 1985. It originated as a generalisation of a Monte Carlo method for examining the equations of state and frozen states of n-body systems. The name and inspiration come from annealing in metallurgy, a technique involving heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. The heat causes the atoms to become unstuck from their initial positions (a local minimum of the internal energy) and wander randomly through states of higher energy; the slow cooling gives them more chances of finding configurations with lower internal energy than the initial one. By analogy with this physical process, each step of the SA algorithm replaces the current solution by a random "nearby" solution, chosen with a probability that depends on the difference between the corresponding function values and on a global parameter T (called the temperature), that is gradually decreased during the process. The dependency is such that the current solution changes almost randomly when T is large, but increasingly "downhill" as T goes to zero. The allowance for "uphill" moves saves the method from becoming stuck at local minima—which are the bane of greedier methods (Goldberg, 1987).

The basic iteration

Each point s of the search space is compared to a state of some physical system, and the function E(s) to be minimized is interpreted as the internal energy of the system in that state. Therefore the goal is to bring the system, from an arbitrary initial state, to a state with the minimum possible energy. At each step, the SA heuristic considers some neighbour s' of the current state s, and probabilistically decides between moving the system to state s' or staying put in state s. The probabilities are chosen so that the system ultimately tends to move to states of lower energy. Typically this step is repeated until the system reaches a state which is good enough for the application, or until a given computation budget has been exhausted.

3. ***Tabu search*** is similar to simulated annealing, (Glover and Laguna, 1997). Tabu search uses a local or neighbourhood search procedure to iteratively move from a solution x to a solution x' in the neighbourhood of x, until some stopping criterion has been satisfied. To explore regions of the search space that would be left unexplored by the local search procedure Tabu search modifies the neighbourhood structure of each solution as the search progresses. The solutions admitted to N * (x), the new neighbourhood, are determined through the use of special memory structures. The search then progresses by iteratively moving from a solution x to a solution x' in N * (x). The most important type of short-term memory to determine the solutions in N * (x), also the one that gives its name to Tabu search, is the use of a Tabu list. In its simplest form, a Tabu list contains the solutions that have been visited in the recent past (less than n moves ago, where n is the Tabu tenure). Solutions in the Tabu list are excluded from N * (x). (Li *et al,* 2004).

*4. **Particle swarm optimization** (PSO):* (maintains a population of solutions rather than a single solution. This algorithm is based on simplified model of social behavior. (Kennedy and Eberhart 1995). The swarm is typically modelled by particles in multidimensional space that have a position and a velocity. These particles ‘fly’ through the search space and has two essential reasoning capabilities: their memory of their own best position and knowledge of their neighbourhood's best, ‘best’ simply meaning the position with the smallest objective value. Members of a swarm communicate good positions to each other and adjust their own position and velocity based on these good positions. There are two main ways this communication is done: a global best that is known to all and immediately updated when a new best position is found by any particle in the swarm. "Neighbourhood" bests: where each particle only immediately communicates with a subset of the swarm about best positions. A single particle by itself is unable to accomplish anything. The power is in interactive collaboration. (Engelbrecht, 2005).

*5. **Ant colony optimization** (ACO):* In the real world, ants (initially) wander randomly, and upon finding food return to their colony while laying down pheromone trails. If other ants find such a path, they are likely not to keep travelling at random, but to instead follow the trail, returning and reinforcing it if they eventually find food. ACO uses many artificial ants (or agents) that incrementally build solutions. Artificial ants deposit artificial pheromones (to this ant-inspired behavior is due their name) that are used by later ants to guide their search. Ant colony optimization is particularly useful for problems where no global or up-to-date perspective can be obtained, and thus the other methods cannot be applied (Dorigo *et al,* 1996)

6. ***Constraint Propagation****:* is based on the concept of using constraints actively to prune the search space. Each constraint has assigned a filtering algorithm that can reduce domains of variables involved in the constraint by removing the values that cannot take part in any feasible solution. This algorithm is evoked every time a domain of some variable and so on (Detcher, 2003).

7. ***Constraint relaxation****:* modifies the relationship defined by a constraint. As the term "relaxation" implies, the modification allows a wider range of relationships. The difference between relaxation of a constraint and non-satisfaction is relaxation makes a particular change in the definition of the constraint, whereas non-satisfaction removes the constraint completely: there is no limit on the values to which the variables can be assigned (Beck, 1994).

APPENDIX F

Publication list

This appendix presents the published work by the author, which are relevant to the topic of this thesis. The title sheets of peer reviewed journal publication are shown, along with the abstract of reviewed conference publications.

F1. PEER REVIEWED JOURNALS

Matthews, J., Singh, B., Mullineux, G., Medland, (2006). A constraint-based approach to investigate the 'process flexibility' of food processing equipment. *Journal of Computers and Industrial Engineering.* **51**(4), 809-820.

Matthews, J., Singh, B., Mullineux, G., Medland, (2007). A constraint-based limits modelling approach to investigate manufacturing machine design capability. *Journal of Mechanical Engineering.* **53**(7-8), 462-477.

Matthews, J (2007). Book review: Manufacturing optimization through intelligent techniques. *Proceedings of IMechE part B*, **221**(4), 759.

Matthews, J., Singh, B., Mullineux, G., Ding, L, Medland, A. J. Food product variation: an approach to investigate manufacturing equipment capabilities. *Food manufacturing efficiency*. 2007, **1**(3) (to appear)

F2. REVIEWED CONFERENCES

Matthews, J., Singh, B., Mullineux, G and Medland, A.J *Methodology for evaluating design capability by use of limits modelling Proc* 6th International symposium on Tools and Methods of Competitive Engineering (TMCE) April 2006, Ljubljana, Slovenia. pp 467-476.

Matthews, J., Singh, B., Mullineux, G., Medland, A.J., ands Hicks, B.J. *Constraint modelling as a means for understanding the limitations of a design and its performance. Proc* 6th International conference on Integrated design and Manufacturing in Mechanical Engineering. (IDMME), May 2006 Grenoble, France. Eds S. Tichkiewitch and M. Tollenaere.

Matthews, J., Singh, B., Mullineux, G., Medland, A.J. A constraint-based modelling approach, to assess the capability of food processing equipment to handle product variation. *Proc of 5th International seminar and workshop on Engineering Design in Integrated Product Development. (EDIPROD*) September 2006, Zielona Gora, Poland. pp95-104.

Matthews, J., Singh, B., Mullineux, G., Medland, A.J. An approach to developing design rules for food processing equipment. *Proc 16th International conference on Engineering Design*. (*ICED07),* August 2007, Paris, France.

Matthews, J., Singh, B., Feldman, J., Mullineux, G., Medland, A.J. Islands of failure in a sea of success: The use of constraints and failure mode maps to assess the capability of machines to handle product variation. *Proc 16th International conference on Engineering Design. (ICED07),* August 2007, Paris, France.

Ding, L., **Matthews. J**., McMahon, C. A and Mullineux, G. An extended product model for constraint-based redesign applications. *Proc International Conference on Engineering Design (ICED07),* August 2007, Paris, France.

Matthews, J., Singh, B., Delandes, A., Mullineux, G., and Medland, A.J. An approach to analyze design configuration of discrete manufacturing system for processing variant products. *Proceedings of Digital Enterprize Technologies (DET2007).* September 2007, Bath, United Kingdom. *Eds* P Maropoulos and S Newman, 637-645. ISBN 978-0-86197-141-1

F3 Journal publication cover sheets

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Computers & Industrial Engineering 51 (2006) 809–820
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Constraint-based approach to investigate the process flexibility of food processing equipment

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Available online 27 October 2006

Abstract

Over the last decade the UK food processing industry has become increasing competitive. This leads the sector to maintain high numbers of product variations. Although some of these products are stable over long periods, others are short lived or seasonal. The ability to handle both the complexity of process and large variations in product format creates extreme difficulties in ensuring that the existing manufacturing, handling and packaging equipment has the process flexibility to cope. This paper presents an approach for investigating the performance envelopes of machines utilizing a constraint modelling environment. The approach aims to provide the engineer with enhanced understanding of the range of functionality of a given machine and provides the possibility of redesign to process variant product.

Keywords: Constraint-based modelling; Process flexibility; Machine analysis; Design knowledge; Food processing

1. Introduction

The research presented in this paper has been commissioned to investigate the capability of food processing equipment to handle product variation. Sethi and Sethi (1990) noted how there are over 50 definitions of flexibility relating to manufacturing. For the purpose of this research process flexibility relates to the ability of equipment to manufacture variant products under the same configuration. Performance is defined as the ability to satisfactorily complete a specified task.

When considering machine capability, the *envelope of performance* (cf. Fig. 1) is the area where the machine will function, using only the inherent design adjustments. This envelope has also been termed as the capacity and capability envelope (Shewchuk & Moodie, 1998). The *envelope of opportunity* is the area where the design will function after external modification to configuration. The approach presented here not only allows the

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Proučevanje konstruiranja proizvodnih strojev s postopkom temelječim na modeliranju omejitev

A Constraint-Based Limits-Modelling Approach to Investigate Manufacturing-Machine Design Capability

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Proizvajalci kupujejo proizvodne stroje, ki so zmožni obdelave nekega izdelka v določenem obdobju. Izdelki, ki se izdelujejo na teh strojih, pa se lahko zamenjajo v dobi trajanja stroja. Proizvajalci se pogosto obračajo na prvotnega proizvajalca opreme, da ocenijo zmožnost prilagoditve stroja na različico izdelka ali celo obdelavo povsem drugega izdelka. V Veliki Britaniji so proizvajalci take opreme majhna podjetja z največ 80 zaposlenimi. S tako omejenimi zmogljivstmi ni zadosti strokovnosti ne časa za izvajanje podrobne analize, kako izboljšati učinkovitost strojev. V preteklosti je bilo zato treba kupiti nove stroje, kar pa je pomenilo velik finančni zalogaj za podjetja, ki so želela predstaviti nove izdelke na že tako konkurenčnem tržišču. Ta prispevek predstavlja postopek raziskave proizvodne zmožnosti nekega stroja. Metodologija sloni na modeliranju omejitev in uporablja možnosti omejenega okolja za modeliranje variantnih oblik in omogoča primerjavo njihove odpornosti na neuspeh. Ta postopek omogoča izdelavo različnih grafičnih predstavitvenih tehnik, ki prikažejo in primerjajo omejitvene pogoje za vse stroje.

(Ključne besede: konstruiranje strojev, prilagajanje izdelkom, modeliranje omejitev, izboljšanje učinkovitosti)

Manufacturers purchase processing machinery, tailor made to handle a specific, limited product range. However, during the life span of the machines, these products are likely to change. The manufacturer often calls on the original equipment supplier to assess the ability of the machines to process either a variant of their existing range or even to consider the handling of a totally new product. In the UK such equipment manufacturers tend to be small concerns, employing 80 staff or less, and with such limited resources that there is not the expertise or time available to perform any in-depth analysis of how well the design operates or what constraints there are that may stop it reaching the new performance requirement. In the past this has led to the manufacturers purchasing new equipment, which puts a high financial burden on companies wishing to introduce new products into already highly competitive market sectors. This paper presents an approach to investigating the manufacturing capability of a machine. The methodology, based on limits modelling, utilizes the capability of a constraint environment to model multiple variations of a design and compare their performances against a range of failure modes. This process allows a variety of graphical visual representation techniques to be created to illustrate and compare the limiting conditions for all machines.

(Keywords: machine designs, product variations, modeling limits, constraints)

0 INTRODUCTION

All process machinery, whether from food processing, automotive sub-component assembly or electrical device sectors, is designed with an innate capability to handle slight variations in the product. This is initially achieved by simply providing tolerances to allow, for example, changes that occur in pack sizes to be accommodated, through user adjustments or complete sets of change parts. By the appropriate use of these approaches most normal variations in product setting can be handled. However, when extreme conditions of setting, major changes in product size and configuration are considered there is no guarantee that the existing machines will be able to cope. The

F4 Conference publication abstracts.

Proceedings of the TMCE 2006

Methodology for evaluating design capability by use of limits modelling

ABSTRACT

The design practices employed within small companies often mean that, they produce machines that are tailored for the specific requirements of a customer. This can lead to an unnecessarily large family of machines, which is supported with large sets of change parts. However the resources are often not available to investigate fully the design and obtain an understanding of its limits. This paper proposes a methodology for investigating the performance limits of a machine. The methodology utilizes the capability of a constraint environment to model multiple variations of a design against given failure modes. This process allows a map to be created to illustrate the limiting conditions for the machine. The actual space of allowable configurations is naturally multi-dimensional. With the allowable space established, it becomes a straightforward process to test whether a given new product is such that it lies within the space and hence can be handled with that machine. It aims to provide the designer with an enhanced knowledge of the range of functionality for a given machine and allows the possibility of redesign to increase this range. The approach is currently being employed to investigate the capability of food processing equipment to handle product variation.

Proceedings of IDMME 2006

Constraint modelling as a means for understanding the limitations of a design and its performance

Abstract:

When new design tasks are undertaken, knowledge of the design area is often ill-understood and the appropriate design rules are unclear. What are more apparent are the constraints which place limits upon the allowable forms of feasible design. This paper looks at a design technique based upon identifying and modelling the underlying constraint within mechanical systems. A design modelling environment is described and it is shown how this has been applied to a range of design task .The types of underlying constraints are discussed together with the ways in which these can be formulated and resolved in the constraint modelling framework. This leads on to a discussion of a constraint-based procedure for identifying and understanding the performance limits of existing and new machine designs. The approach is illustrated by a number of case study examples taken from the design of packaging and food processing machines. The typical constraints underlying such examples are discussed as well as the performance measures used to improve performance.

Proceeding Design2006

Embedding general constraint resolution into a CAD system

Computer aided design (CAD) has facilitated designer's task by automating many of the activities involved in a conventional design process. This can be further augmented by use of constraints in CAD systems. However there is still need for incorporating general constraints. This paper highlights some of these constraints. Constraint modeller software that incorporates these constraints is described here. Based upon this constraint modelling approach, a new constraint modeller-CAD interfaced system has been created. This system can offer combined advantages of these two systems and has been demonstrated in modelling, assembling and simulating the action of part of a confectionary wrapping machine.

Keywords**:** *CAD, constraints, design*

Proceedings EDiPROD2006

A constraint-based modelling approach, to assess the capability of food processing equipment to handle product variation

Abstract: *For design and development engineers, difficulties arise ensuring that existing manufacturing equipment has the potential to handle both large product variation and complexity of process. The food processing industry maintains the highest number of product variations, some of which are short lived or seasonal, a factor with which the processing equipment has to cope. This paper presents the idea of "constraint modelling", and identifies it employment in the investigation of the capabilities and optimized performance limits of such equipment. The paper also introduces the concept of multi-instance modelling and its benefits. The approach being employed is illustrated by a number of industrial case study examples, taken from the food processing industry.*

"ISLANDS OF FAILURE IN A SEA OF SUCCESS": THE USE OF CONSTRAINTS AND FAILURE MODE MAPS TO ASSESS THE CAPABILITY OF MACHINES TO HANDLE PRODUCT VARIATION

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ABSTRACT

The approach described here utilises the capability of a constraint modelling environment to map the failure modes of a design. At this stage the modeller can be employed to explore possible design variations against a given goal which does not violate the failure modes. Mapping of the failure modes gives the designer enhanced knowledge of which modes are invoked under certain processing scenarios. This allows the designer to modify the design so that it lies in an area away from the failure mode. The combined failure maps illustrate the functional boundary of a design under variation.

Keywords*: Failure mode maps, constraint-based modelling, processing equipment, design knowledge, mechanisms*

AN EXTENDED PRODUCT MODEL FOR CONSTRAINT-BASED REDESIGN APPLICATIONS

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ABSTRACT

This paper presents an extended product model to support the constraint-based redesign process of production machinery to handle product variation. The paper highlights the deficiencies of existing product models (e.g. CAD models), namely such models provide good geometrical and topological information, but offer limited support information for the redesign process, specifically excluding factors such as, performance capabilities, constraints, and the reasoning behind decisions. The research aims to encapsulate the information generated during the redesign process within a new extended product model, so that it can be revisited throughout the whole product life. The proposed extended product model expands current CAD models beyond physical entities, including geometrical and topological information, performance limits, alternative concepts and solutions, and change parts. It adopts a hierarchical structure, to provide specific levels of detail, according to different specialist expertise and stages in the product lifecycle. It also defines the model elements with design constraints, design activities, supporting resources, decisions made and design rationale in the redesign process, no matter what type of document is used. The proposed extended product model is illustrated with a case study example from the food industry.

Keywords*: Extended product model, constraint-based design, constraints, design information.*

AN APPROACH TO DEVELOP DESIGN RULES FOR FOOD PROCESSING EQUIPMENT

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ABSTACT

The complexity of food production stems from the diverse nature of the products. These range from large solids through to liquids and pastes. Their processing is itself also diverse: from simple assembly processes of liquids and solids through to the control of complex chemical and cooking processes. Commercial pressures mean food companies must continually reinvent and evolve their products, creating large product families. The ability to handle both the complexity of process and large variations in product format generates extreme difficulties in ensuring that the manufacturing, handling and packaging equipment can cope. This paper presents a methodology built on the understanding of the relationships between food product features and processing factors. The methodology offers the designer the possibility to redesign the processing equipment from knowing the bounds of the product features and also to reverse engineer the product from the bounds of the process. The paper also presents research findings, showing a taxonomy of food stuffs, and taxonomy of food product-process relationships. Validity relationships from this taxonomy can be used to model the product. In addition to this the limiting factors of food processing equipment are identified, these factors must be implemented in the modelling and simulation of the equipment. The methodology and its application is presented with some industrial case studies

Keywords: *food product features, food processing equipment design, design constraints, design rules, variant design*

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AN APPROACH TO ANALYZE DESIGN CONFIGURATION OF DISCRETE MANUFACTURING SYSTEM FOR PROCESSING VARIANT PRODUCTS

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ABSTRACT

For years manufacturers have relied on trial and error approaches to develop their existing machine range to process new or variant products. The approach presented in this paper, employs the capability of a constraint-based modelling environment to model and simulate variations in machine design configuration and assess their ability to process variant products.

Keywords: *Process modelling, product variation, manufacturing systems evolution,*